Measures to utilize real-time gas quality analyses for engine control

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Master's thesis

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ABSTRAKT

Intresset för att använda naturgas som bränsle i förbränningsmotorer har växt de senaste åren. Fördelarna med att använda naturgas kan ses i ekonomi och miljöaspekterna. Däremot varierar naturgasens komposition mycket över hela världen och ändrar även med tiden. Detta medför utmaningar för motortillverkare med tanke på designen och optimeringen av motorerna gällande bränsleförbrukning, pålitlighet och utsläppskrav.

I normala fall optimeras en motor utgående från vad kunden har specificerat gällande det bränsle motorn är tänkt att köras på. Detta arbete grundar sig i hur naturgasens kvalitet, som mäts i ett så kallat metantal, kan användas för att styra motorns förbränning i realtid. Med en kontrollfunktion baserad på gaskvalitet elimineras behovet att låsa motorns prestanda till en viss typ av gas. Målet med föreliggande examensarbetet var att undersöka hur gasens kvalitet inverkar på förbränningen, och med denna information bestämma med vilken kontrollfunktion gaskvalitetens iverkan kan motverkas.

Utvecklingen av kontrollfunktionen gjordes i form av studier av data från en testinstallation i Danmark samt genom motortester i laboratoriemiljö. Som bistudier undersöktes en ny typ av gassensorteknologi, och samtidigt gjordes en prestandaberäkningsstudie för ett referensgasprojekt.

Dataanalysen visade att den elektriska verkningsgraden påverkas negativt av högre metantal än vad motorn är optimerad till. Å andra sidan påverkades verkningsgraden positivt av lägre metantal, och hade då högre knacknivåer och förhöjda kväveoxidutsläpp. Den testade kontrollfunktionen visade sig vara lämplig för att förhindra problem med knackförbränning vid sämre gaskvalitet samt höja verkningsgraden vid högre metantal.

Nyckelord: Gasmotor, naturgas, metantal, gaskvalitet, motorstyrning

ABSTRACT

The interest to use natural gas as fuel in internal combustion engines has grown in recent years. The benefits of using gas as a fuel can be seen both in the economic aspects and in the environmental aspects. However, the composition of natural gas differs considerably around the world and changes with time. This brings challenges for engine producers regarding design and optimisation of engines for lower fuel consumption, reliability and emission regulations.

In normal cases, an engine is optimised according to what fuel the engine will be operating on. This thesis focuses on how the quality of natural gas, measured in a so-called methane number, can be used to tune the engine in real time. With a control function based on gas quality the need to lock engine performance to a set gas is eliminated. The main goal of the work is to evaluate how the gas quality affects the combustion, and with this information determine what kind of control function would be suitable to counteract the quality impacts.

The development work was done in the form of data analysis from a test installation in Denmark and engine experiments in laboratory environment. As side studies a new type of gas sensor was tested and evaluated, while a performance calculation for a reference gas project was made as another part study.

The results from the data analysis showed that the electrical efficiency is lower when the engine is operating on a higher methane number than compared to what methane number it is tuned to. However, the efficiency is higher at lower methane numbers, with higher knocking levels and higher nitrous oxide emission levels. The control function that was tested proved to be suitable for preventing knocking combustion with lower methane numbers and increase the efficiency at higher values.

Key words: Gas engine, natural gas, methane number, gas quality, engine control

TABLE OF CONTENTS

PREFACE

This thesis work was conducted within a research and development project for Wärtsilä Finland Oy during 2018, a quite challenging task regarding a very interesting subject.

With these words I would like to thank those who have been part of this project and providing support, your help has been very valuable. A special thanks to Kaj Portin for giving me the opportunity to work with this subject. Also, I would like to thank Cataldo De Blasio and Margareta Björklund-Sänkiaho at Åbo Akademi Univeristy for giving me valuable feedback about the writing and thesis structure.

Vasa 12.9.2018
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LIST OF SYMBOLS AND ABBREVIATIONS

$\dot{m}_a$	Air mass flow
$\dot{m}_f$	Fuel mass flow
$IMEP_g$	Gross indicated mean effective pressure
$IMEP_n$	Net indicated mean effective pressure
R_{bs}	Bore to stroke ratio
$\dot{V}$	Volume flow
V_c	Clearance volume
V_d	Swept volume
$W_{c,ig}$	Gross indicated work per cycle
W_p	Pumped work per cycle
c_p	Heat capacity
g_s	Specific gravity
n_r	Number of crank revolutions per power stroke
r_c	Compression ratio
A/F	Air to fuel ratio
B	Piston bore
BDC	Bottom dead centre
CAN	Controller area network
DF	Dual fuel
L	Piston stroke length
LHV	Lower Heating Value
MN	Methane Number
N	Rotational speed
P	Power
PCC	Pre-combustion chamber
PLC	Programmable logic controller
RCM	Rapid compression machine
SG	Spark-ignition gas
T	Torque
TDC	Top dead center

WI	Wobbe index
WKI	Wärtsilä knocking index
WMN	Wärtsilä Methane Number
η	Efficiency factor
Θ	Temperature
λ	Relative air to fuel ratio
$BMEP$	Break mean effective pressure
$PMEP$	Pumped mean effective pressure
V	Volume
$bsfc$	Break specific fuel consumption
p	Pressure
κ	Thermal conductivity

1 INTRODUCTION

In the current, rapidly growing world, emphasis is being placed on sustainable and new, greener technologies. Among these, emission-free ways to produce electricity, solar, wind and water power are perhaps seen as the most promising ones. However, the road to a totally emission-free power generation is long, and the conventional production methods will be present for some time still. Research is therefore not only focused on renewable energy sources, it is also directed at improving the ones that are already available. At Wärtsilä, gas-fired engines have been produced for over 20 years and they will not be phased out anytime soon. Reliability is of key importance in an engine i.e. the reliability to run the engine continuously without interruption, and in an efficient way. To remain reliable and efficient, the possibility to handle changes in incoming gas quality is essential for a gas engine, and with the growing fuel market, and larger diversity in gas distribution, the importance of reliability grows even stronger. This thesis project revolves around these earlier mentioned gas engines, the fuel they operate on, how the engines react to different fuels and, most importantly, how they can be controlled effectively regarding changes in the incoming fuel quality.

The benefits of using real-time readings of gas quality for engine control can basically be divided into two topics. With a well-functioning control, the engine should be able to handle lower-quality gas without the need to decrease the load because of knocking combustion. Secondly, engine parameters should always be optimised to the best possible efficiency, which means running just below knocking limits. With this control function, the operating area would be widened with improved efficiency. In addition, the measuring of the incoming gas could also be of interest for the operator from an informational perspective.

The scope of the project is divided into two main topics that are treated in this thesis. To start, gas- and engine data are studied to determine how gas quality affects engine efficiency, knocking behaviour and emissions. Based on these results a control functionality is tested on a laboratory engine with a parameter tuning based on changing gas quality, in this case between pre-determined compositions.

As a side study, a new gas-sensing technology is studied and tested both at a fuel and an engine laboratory. Another side study is also conducted on engine test data, to investigate the idea of a possible reference gas and how it could be utilised as a standard to which engine makers would report their engine performance.

Although Wärtsilä manufactures engines that can operate on both diesel and gaseous fuels, this project has been limited to the pure gas, spark-ignited engines, since almost all previous development within the internal project revolves around this kind of engine. It is, however, not limited to one engine model, design stage or size.

2 LITERATURE REVIEW

Engine performance is highly connected to the quality of the fuel and the way it is combusted within the cylinder. To ensure a reliable operation, these should be known and preferably also counteracted. To obtain a better understanding of how different fuel properties affect the behaviour of a gas-fuelled engine, this chapter will cover the working principle-, combustion process- and parameters of gas-fuelled engines. Gaseous fuel properties and qualities, how they affect the combustion, will be reviewed. Lastly, a previous study on the subject will be presented to provide some background to the internal project.

2.1 Gas engine fundamentals

The gas engine operates by a series of operations, called the Otto cycle. Premixed air and fuel enter the combustion chamber through an inlet port, where the mixture is compressed to a higher pressure and temperature. A heat source, spark ignition, or pilot injection ignites the mixture. After the combustion, the exhaust gases leave the cylinder through an exhaust port. These steps occur during four so called strokes, described below and shown in Figure 1.

1. Intake stroke. The intake stroke starts with the piston at the top dead centre (TDC), as the piston moves downwards, the fuel/air mixture enters the cylinder. The inlet valve that controls the inflow of gases opens as the stroke starts and closes at the end of the stroke.

2. Compression stroke. With all valves shut, the piston starts moving upwards from the bottom dead centre (BDC), compressing the fuel/air mixture. Just before the end of the compression stroke the gas mixture is ignited, increasing the cylinder pressure rapidly.

3. Power stroke. The high pressure formed by the expanded gases pushes the piston and connecting rod down, forcing the crank to rotate. When the piston reaches the BDC, the exhaust valve opens, decreasing the cylinder pressure and beginning the exhaust process.

4. Exhaust stroke. Some of the gases are forced out of the cylinder due to the temporary pressure difference between the cylinder and exhaust pressure. The remaining gases are pushed out as the piston starts moving upwards again. As the piston approaches the TDC, both inlet and exhaust valves are open, and the rest of the burned gases are forced out by the incoming mixture.

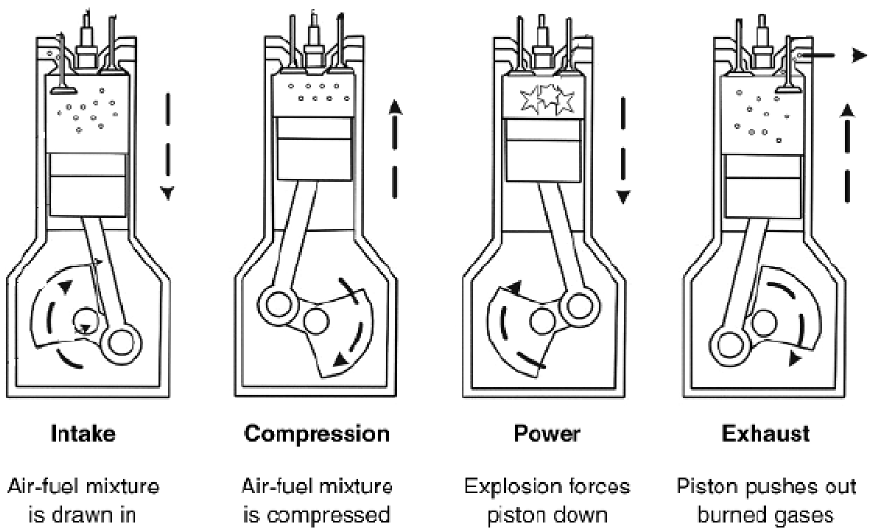

Figure 1 Otto engine working cycles (Fallah, Khajepour & Goodarzi, 2016)

2.1.1 Combustion technologies

In theory, the fuel and air mixture will be ignited at the top dead centre and combust instantaneously, or in other words at a constant volume. In reality this is not true, since ignition is typically initiated around 15 crank angle degrees (CA°) before TDC and combustion lasts about 25 CA°, Figure 2, for Wärtsilä gas-fired engines. This makes the curve of the real cycle look slightly different at the point of peak pressure, as seen in Figure 2.

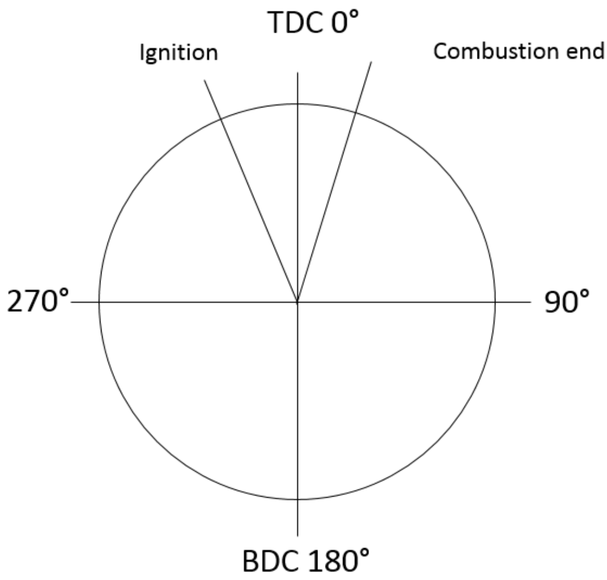

Figure 2 Ignition timing and combustion duration (Heywood, 1988)

In comparasion to the Otto cycle, the Diesel cycle operates in a slightly different way. In the ideal case, the diesel injected at the TDC will ignite and combust at a constant pressure as the piston starts moving downwards. Again, the real case does not resemble the ideal principle, which can be seen in Figure, 3, where a clear pressure rise can be seen as the first fuel is ignited (Hattar, 2005).

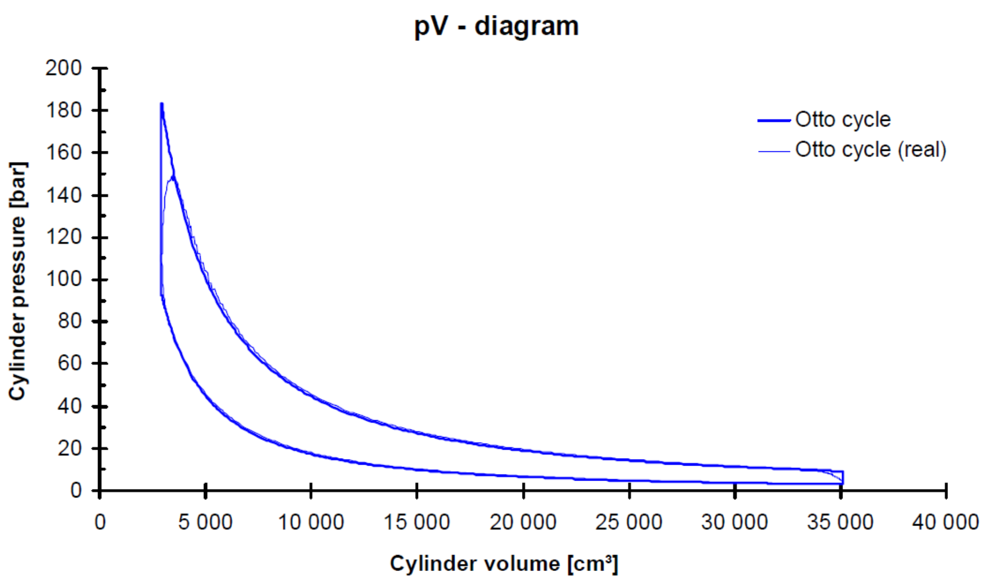

Figure 3 pV-diagram of an ideal and real Otto cycle (Hattar, 2005)

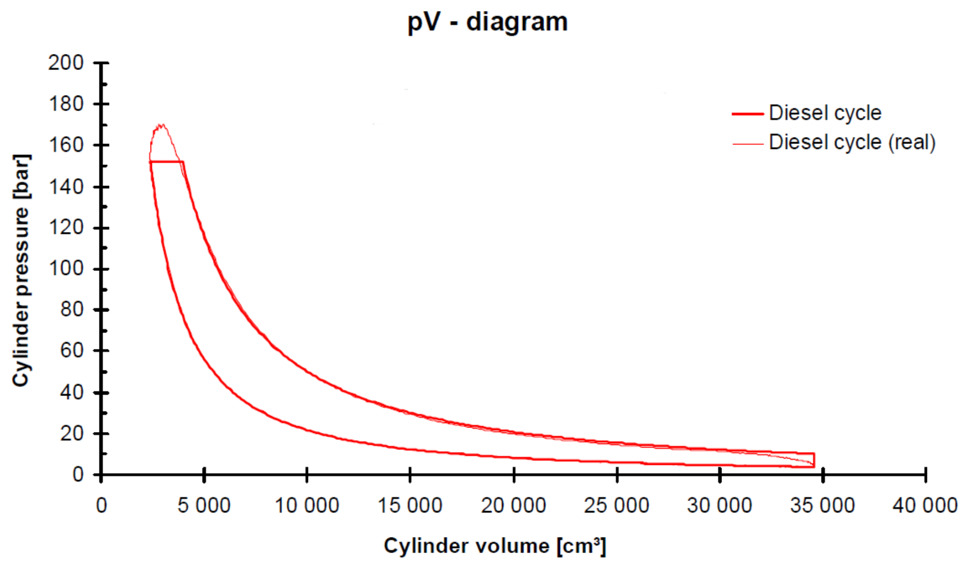

Figure 4 pV-diagram of an ideal and real Diesel cycle (Hattar, 2005)

In Wärtsilä engines, two different techniques are used for fuel ignition. For spark ignited engines (SG), the combustion is initiated by a sparkplug. This sparkplug is placed inside a pre-combustion chamber (PCC), which holds a richer, more easily ignitable mixture of fuel and air, Figure 5. The pre-combusted gases act as the heat source for the process and are directed from the PCC, through a nozzle, to the main combustion chamber (Hattar, 2005).

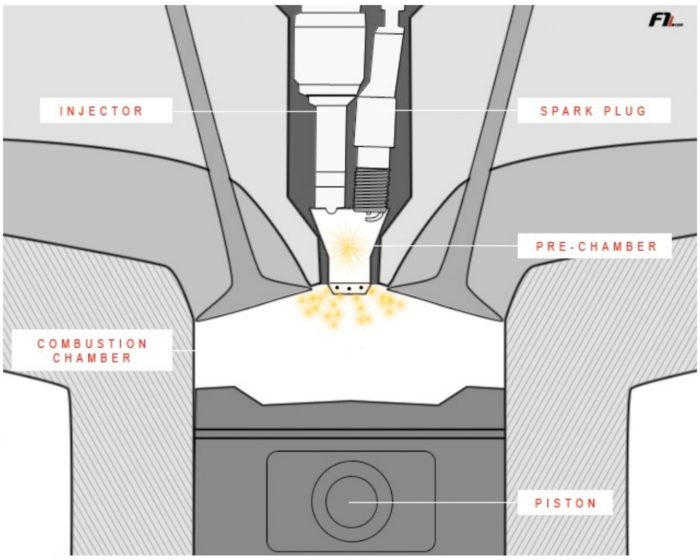

Figure 5 Precombustion and main combustion chamber for a lean burn engine (F1i magazine, 2016) see also (Slefarski, Golebiewski, Czyewski, Gizymislawski, & Wawrzyniak, 2018)

The second method of igniting the gas/air mixture is called compression ignition. This is used in Wärtsilä dual fuel engines (DF) and pure diesel engines. In this case a fuel injector injects a small amount of diesel fuel into the gas filled combustion chamber. As the temperature inside the cylinder is higher than the auto-ignition temperature of the diesel fuel, it ignites, starting the combustion. The same fuel injector is also used when the engine is operating in diesel mode and using liquid fuel (Heywood, 1988).

2.1.2 Operating parameters

Engine parameters are quantities that tell the characteristics of an engine. Rated power, P (kW) and torque, T (Nm) are perhaps the most common ones. Torque is usually measured using a dynamometer and rated power is calculated as

$$\mathrm{P_b} = 2\pi\mathrm{NT}, \tag{1}$$

where N is the rotational speed (1/s) of the engine (Heywood, 1988). Comparing different engines using these is not fair in the sense that they do not reveal anything linked to the engine's performance, as bigger engines produce more power than smaller ones, but not necessarily at a lower fuel consumption per output.

From an operational point of view the fuel consumption is probably of interest. This may be defined directly as a mass-flow per time unit, $\dot{m}_f$ (kg/h), but more often it is normalised to engine power output. This is called specific fuel consumption, or brake specific fuel consumption, bsfc, and is normally expressed as g/kWh and defined as

$$bsfc = \frac{\dot{m}_f}{P_b} \tag{2}$$

(Heywood, 1988). Some of the parameters are so-called geometrical properties and are directly connected to the engine design. The first one is called compression ratio r_c. This indicates the volume ratio to which the air-fuel mixture is compressed, calculated according to Eq.(3), where V_d is the swept volume, and V_c is the clearance volume. Another term that is related to the general measures of the engine components is bore to stroke ratio, R_{bs}, calculated according to Eq.(4), where B represents the piston diameter and L the piston stroke length. Figure 6 illustrates the positions of the geometrical properties used in the calculations (Heywood, 1988).

$$r_c = \frac{V_d + V_c}{V_c} \quad , \quad R_{bs} = \frac{B}{L} \tag{3,4}$$

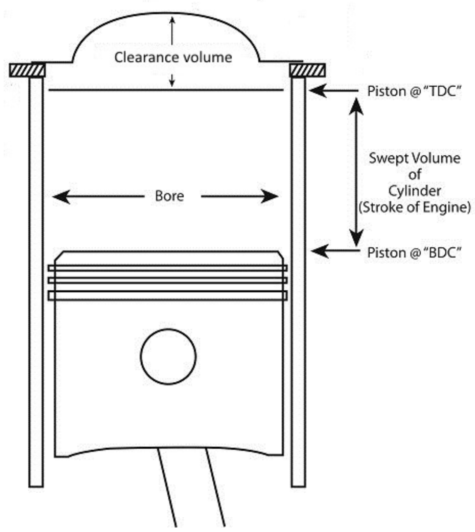

Figure 6 Visualisation of geometric engine parameters (J&P Cycles, 2018) see also (Heywood, 1988)

A good way to determine the performance of an engine is to look at the brake mean effective pressure, BMEP (kPa), but usually converted to (bar). this indicates how much work is done by the cylinder volume per cycle.

$$BMEP = \frac{P_b n_r}{V_d N} \tag{5}$$

n_r tells the number of crank revolutions per each power stroke, two for four stroke engines. Since BMEP is obtained using the power output from the engine, it takes all the frictional and auxiliary losses into account. If the losses related to power transmission and auxiliary equipment of the engine are disregarded, there is another way to gain an understanding of how efficient the combustion itself is. The volume and pressure changes inside the cylinder can be plotted into a p,V-diagram, Figure 7.

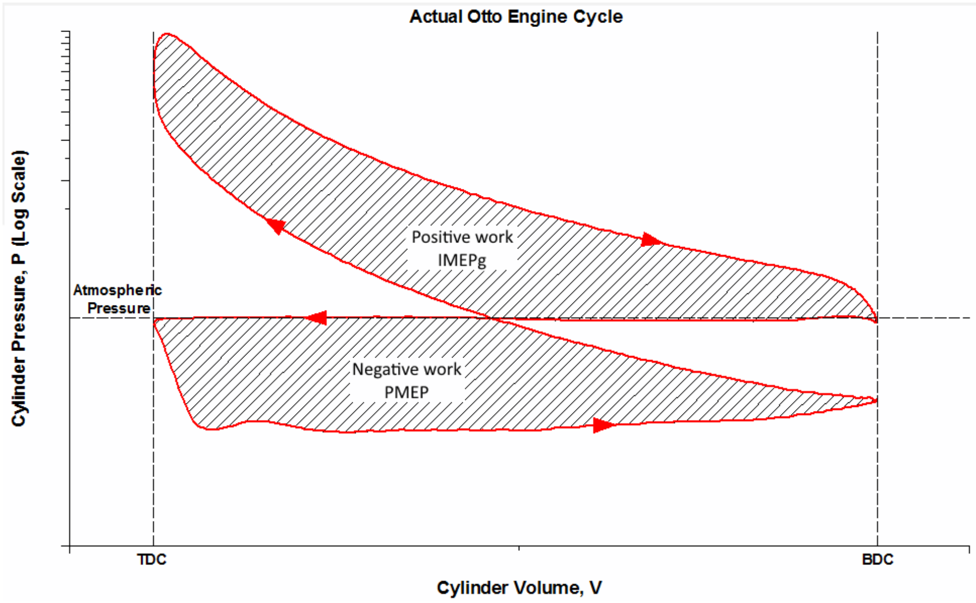

Figure 7 p,V diagram for a four-stroke cycle (Engine knowhow, 2018)

By integrating these two curves from top dead centre to bottom dead centre, two parameters can be obtained. The first one is gross indicated work per cycle, $W_{c,ig}$. This, upper, dashed area in Figure 7 represents the compression and expansion stroke, i.e. work delivered to the piston.

$$W_{c,ig} = \int_{BDC}^{TDC} p_{\,positive-work\ curve}\, dV \tag{6}$$

By integrating the low-pressure, curve, W_p, pumping work is acquired, represented by the lower, dashed area. This is work done by the piston during gas exchange in the inlet and exhaust strokes:

$$W_p = \int_{BDC}^{TDC} p_{\,negative-work\ curve}\, dV \tag{7}$$

Dividing these two (6,7) with the swept cylinder volume gives corresponding mean effective pressures, $IMEP_g$ and $PMEP$.

$$IMEP_g = \frac{W_{c,ig}}{V_d} \quad , \quad PMEP = \frac{W_p}{V_d} \tag{8,9}$$

Subtracting the pumped pressure from the gross indicated pressure gives the net indicated mean effective pressure as result (10). $IMEP_n$ express the net amount of work that is transferred from the gases to the piston, and in that sense how efficient the combustion is:

$$IMEP_n = IMEP_g - PMEP \tag{10}$$

In normal operation mean effective pressures are not that interesting, but for an engine developer these are thought of every day. In laboratory environments external hard and software are used to determine for instance IMEP, combustion duration using pressure sensors and angular position of the engine.

A more direct, and very common approach to engine efficiency is to simply study the rated output and the amount of energy that is delivered to the engine by the fuel. This gives a unit-less value called efficiency factor

$$\eta = \frac{P_b}{\dot{m}_f Q_{LHV}} \tag{11}$$

with Q_{LHV} as the lower heating value which expresses the energy content of a fuel on mass basis (kJ/kg), $\dot{m}_f$ as mass flow (kg/s) and P_b power output in kW (Heywood, 1988). Normally, in daily talk, heating values are referred to as LHV and HHV. The difference between higher and lower calorific values of a fuel is whether the energy needed for water vaporisation is considered or not. Regarding engine technology, the fuel energy that is “stolen” to vaporise the water contents of the fuel cannot be used to drive the engine, and therefore LHV is almost excludingly used.

As stated earlier, fuel and air enter the cylinder pre-mixed. The ratio between the two components is a relevant operating parameter. Normally both air mass flow and fuel mass flow are measured, and the air/fuel ratio is calculated on a mass basis as:

$$A/F = \frac{\dot{m}_a}{\dot{m}_f} \tag{12}$$

The ideal mix is achieved when all the available fuel reacts with all the available oxygen, leaving no excess air, referred to as a stochiometric ratio. For natural gas the ratio is about 17:1. In engine applications the A/F ratio is usually expressed as a factor lambda, (λ), describing the relation between the actual versus the stochiometric A/F-ratio, which better indicates the state of the mixture than the actual air to fuel ratio (Heywood, 1988):

$$\lambda = \frac{A/F_{actual}}{A/F_s} \tag{13}$$

For an ideal mixture, λ is equal to 1. With λ higher than 1 the mixture is lean, and with λ lower than 1 the mixture is referred to as rich, meaning that there will be unburned fuel left in the exhaust gases. Automotive engines operating on gasoline traditionally use a feedback control on the lambda value to keep it at 1 (Korakianitis;Namasivayam;& Crookes, 2011).

Lean-burn engines, like Wärtsilä gas engines, run at a higher value, around 2.1. This allows for a more complete combustion at a lower temperature, which increases efficiency while decreasing NO_x emission, since the combustion temperature will be kept lower. In addition, hydrocarbon and carbon monoxide emission formed by incomplete combustion are reduced. In Figure 8, it is shown that the operating window, limited by the misfiring and knocking regions, grows narrower when going towards higher BMEP (load) and efficiencies (Heisler, 1995).

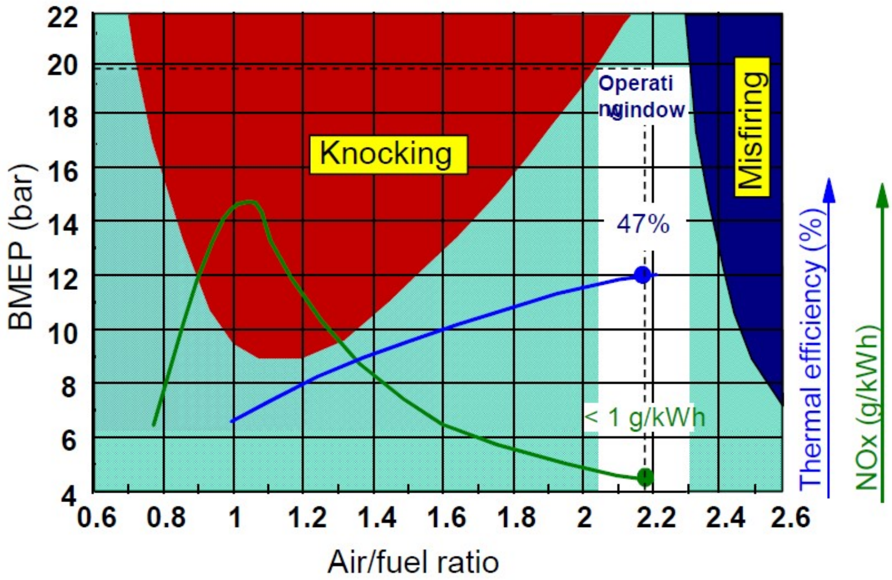

Figure 8 Operating window of a leanburn gas engine (Hattar, 2005)

2.2 Gaseous fuel characteristics

Since gaseous fuels are produced worldwide, at different locations and using different methods, they vary in composition and quality. As new technologies drive the market into more sustainable fuels and unconventional sources, these variations increase further.

2.2.1 Natural gas

Currently, natural gas is by far the most used type of gas in combustion engines. In land-based installations, gas is usually transported using pipelines and for marine applications, it is stored as liquified natural gas (LNG), compressed to around 1/600 of its original volume at normal temperature and pressure. The majority, 70-95% of the natural gas is composed of methane (CH_4). While some smaller quantities of the heavier hydrocarbons can be found, usually in the form of ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}) and penthane (C_5H_{12}). The rest of the composition is usually made up of inert gases, like carbondioxide (CO_2) and nitrogen (N_2). Common ranges can be seen in Table 1.

Table 1 Natural gas components and typical ranges in vol-% (Speight, 2008)

Gas	Formula	Range
Methane	CH_4	70-90%
Ethane	C_2H_6	0-20%
Propane	C_3H_8	
Butane	C_4H_{10}	
Pentane and higher hydrocarbons	C_5H_{12}	0-10%
Carbon dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen sulphide	H_2S	0-5%
Rare gases	A, He, Ne, Xe	trace

One of the main drivers for the increased use of natural gas would be the low emissions. Natural gas has the lowest CO_2 footprint of all the fossil fuels (Demirbas, 2010). This is mainly because it, on a mass basis, contains the lowest amount of carbon, compared to traditional fuels. This can be explained by studying the governing chemical formula for alkanes, Figure 9, and the ratio between carbon and hydrogen molecules. In general, natural gas consists of alkanes up to C_6, which gives it a low carbon mass percentage compared to petroleum fuels.

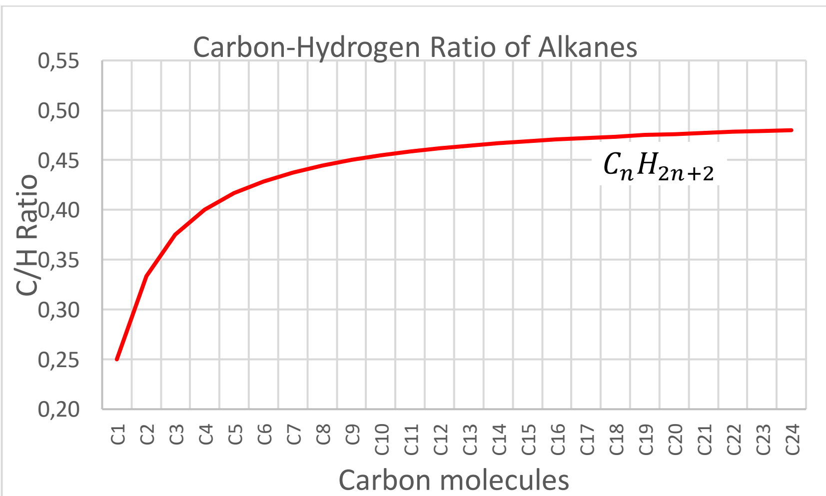

Figure 9 Carbon-to-Hydrogen Ratios of Alkanes

Regarding the low nitrogen content of the fuel, fuel-NO_x formations become insignificant. This combined with lean-burn technologies, result in significantly lower NO_x emission levels compared to diesel engines, because of the lower compression ratio and therefore lower combustion temperature. Sulphur oxide emissions, (SO_x), are at the same time reduced to zero, since natural gas does not consist of any sulphur (Demirbas, 2010).

2.2.2 Fuel properties

The main property for a fuel in general is the energy content, this includes gases as well. But what differentiates gases from liquid fuels, is that instead of comparing the fuel according to ignitability, it is measured in knock resistance. Knocking will be described in the following chapters, but in principle knock resistance is the inverse of ignitability.

For the energy content, the lower heating value, LHV, is usually used to indicate how much heat is released per mass or volume unit during the combustion, often expressed as MJ/kg or MJ/m^3. In opposition to the higher heating value, HHV, this calculation assumes that the heat used to vaporise water formations is not recovered. Heating values can either be measured or calculated from the gas composition, if its known.

To characterise knock resistance a methane number is used. There are several different calculation methods available, most of them based on the AVL methodology. In this project, the Wärtsilä Methane Number (WMN) will primarily be used. The WMN was developed in cooperation with DNV GL, to enable better knock predictions for modern engines, and new fuels. The development of this calculation tool will be described in more detail further on (van Essen & Gersen, 2018).

A parameter often used by gas suppliers to define interchangeability of fuel gases is the Wobbe index (WI), which is related to the heating value and specific gravity. In principle, two gases with identical Wobbe indices, with set pressure and valve settings, will give identical energy output. This information is useful, to minimize the impact of gas supply fluctuations. Since heating values can be expressed as either lower or higher, the Wobbe index can also be presented as either high or low. In general, WI is most commonly calculated with LHV and specific gravity, g_s, according to Eq.(14) (Demirbas, 2010).

$$WI = \frac{LHV}{\sqrt{g_s}} \tag{14}$$

Some other properties that might be of interest from a combustion point of view are:

- Ignition point – at what temperature the gas auto ignites at normal pressure.
- Flammability limits – expressed as volume percentage in air, at which the mixture is ignitable.
- Theoretical flame temperature – the temperature that would be achieved if all available energy would be used to heat up the flame.
- Maximum flame velocity – the highest velocity the expanding flame front of a specified gas can achieve. (Demirbas, 2010)

2.2.3 Gas production and availability

As the economy is growing and the interest in natural gas also increases, new and more unconventional sources of natural gas will be introduced. With the LNG infrastructure expanding globally, new suppliers will enter the market, bringing on new challenges. At the same time, end users of pipeline gas will experience larger numbers of suppliers feeding the pipeline system, all of which differ in quality and properties. Figure 10 shows that on a global level, the Middle East is the largest producer of LNG and that Russia the biggest pipeline gas exporting country. This will probably be the case also in the future. But with more producers entering the market, variations in quality are predicted to increase.

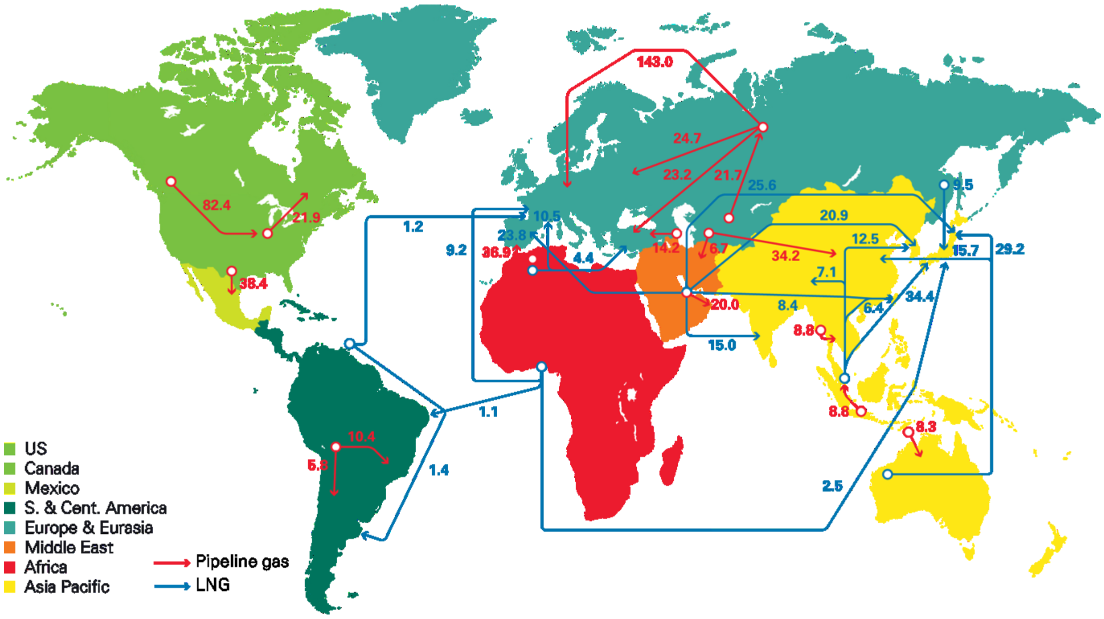

Figure 10 P Natural gas infrastructure (Statistical Review of World Energy, 2017)

Regarding methane number, the overall LNG volume will shift towards higher numbers, with a mean value over 80 by 2027. Mainly contributed by new sources in the US, Canada, Middle East and Africa. The share of low methane number gas is however expected to remain significant in Australia and Southeast Asia. Increasing methane numbers is mainly considered a good thing, but as the engines are tuned towards higher efficiency and outputs, it makes them more sensitive to "bad" gas. Today, gas engines are often sold and optimised to the worst possible gas quality the customer has stated, independent of, how many days per year it will operate on the mentioned quality. This is where the advantages with real-time gas measurements shines the brightest, allowing the engine to adapt to changes in the incoming gas (Koot, Future LNG Quality Study, 2018).

2.2.4 Development of Wärtsilä Methane Number

Ranking of natural gas according to its ignitability using a methane number has been the practice since the 1970's. Most of the gas suppliers as well as engine manufacturers use their own adaptions, based on the final work and data published by AVL in 1971. This old method uses a methane-hydrogen scale, with number 100 being the knock equivalent of pure methane, and 0 assigned to hydrogen. The scale is based on a complex interpolation procedure, using ternary diagrams, which makes it a bit outdated for modern technologies. Another disadvantage with the AVL method, is the uncertainty around the handling of sustainable fuels containing CO_2, CO, H_2 and higher hydrocarbons, C_{4+} (Andersen, 1999).

The main motives for the development of a new tool were the trending towards higher break mean effective pressures, ultra-lean burn engines and higher performance, which knocking puts a limit on, because of the higher firing pressures. A better method was needed for these modern engines and 'new' fuels that allows for higher performance on a broader range of fuels. One key requirement was to have a straightforward algorithm, that could easily be integrated for fuel-adaptive control systems. Based on these requirements, a decision to develop a gas rating tool 'calibrated' to the latest engine technologies was made. For this purpose, tests were conducted on a W34SG engine, with 340mm bore and 400mm stroke, to deliver specific data on the relations between fuel gas composition and knocking behaviour. By request, DNV GL was the partner assigned to build the calculation tool. The approach was to develop a combustion phasing model, using engine specific details, thermodynamics and chemical kinetics to get corresponding pressure profiles for the simulation and measured pressures for different gas compositions. The next step was to develop an ignition model with the correct autoignition chemistry, where a Rapid Compression Machine (RCM) was used. With an accurate simulation, end-gas auto ignition could be modelled by increasing the intake air manifold temperature.

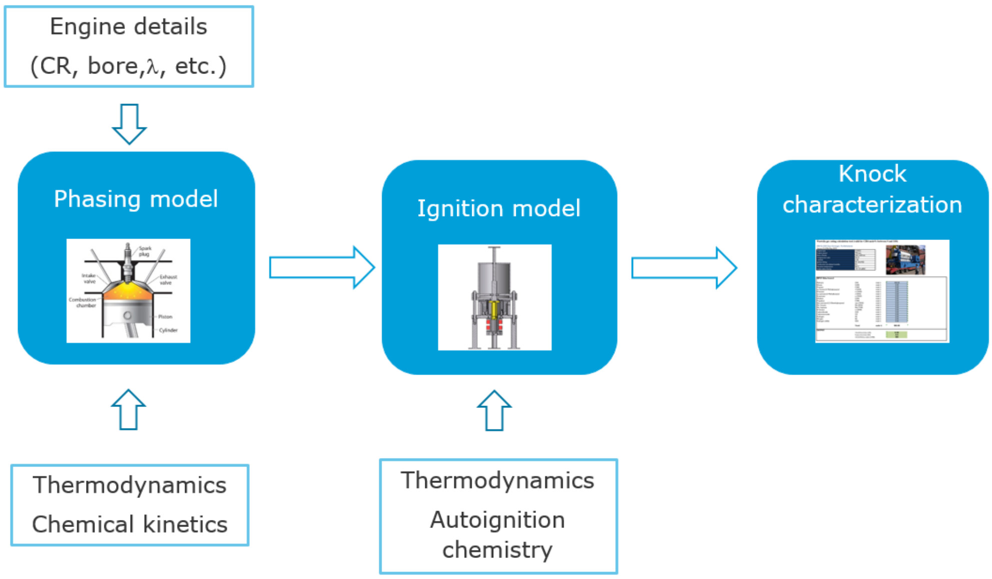

Figure 11 Modelling process of knock characterization (van Essen & Gersen, 2018)

To compare the knock resistance of a gas mixture, a n-Pentane scale was used, referred to as Wärtsilä Knocking Index (WKI). This index expresses the equivalent fraction of n-Pentane in Methane under the same engine conditions, and is a straight forward polynomial equation. The WKI was further-on converted to a 0-100 methane number scale (van Essen & Gersen, 2018).

$$WKI = \sum \alpha_{i,n}\, x_i^n + \sum \beta_{i,n}\, x_i^n x_j^m \tag{15}$$

$\alpha_{i,n}$ = Binary coefficient for component i and exponent n.

x_i = Share of component i, 0 to 1.

n = Binary exponents = 1, 2, 3 and 4.

$\beta_{i,j,n}$ = Ternary coefficient for components i and j, and exponent n.

x_j = Share of the second component j in the ternary mix.

m = Ternary exponents = 1, 2 and 3.

where the binary part states how much an individual gas, for instance methane, contributes to the methane number. The ternary coefficients states how the reaction between two gases, for instance methane and ethane, contributes to the overall methane number.

2.3 Engine knocking

Abnormal combustion events, such as knocking, can have severe effect on engine performance, and even lead to potential damage if not controlled correctly. Knocking is the name given for the noise that is transmitted through the engine structure, when a spontaneous combustion ahead of the flame front occurs. When this happens, there is a rapid release of chemical energy in the end gases, which leads to substantially higher, local, pressure pikes, and propagation of pressure waves throughout the combustion chamber. In normal operation, end gases inside the combustion chamber will be consumed by the propagating flame front, and the fuel air mixture will be burned as it moves outwards from the ignition point. In this case, the end gas temperature is lower than the temperature at which the gas blend auto ignites. The risk of end gas knocking increases with the rising temperatures inside the combustion chamber.

Knocking is best illustrated in form of a pressure-crank angle diagram. In Figure 12.a normal combustion, 12.b light knock, and 12.c heavy knocking is shown. These curves are taken from a real engine test, and show the characteristic pressure waves that occur when knocking takes place. As expressed in these pictures, heavy knocking occurs closer to the top dead centre, which is the vertical line in Figure 10, and result in larger amplitude fluctuations. If knocking is left unattended, even for a shorter period, it can lead to severe engine damages. To prevent seizures, engines are usually equipped with safety systems, that shuts the engine down when heavy knocking occurs.

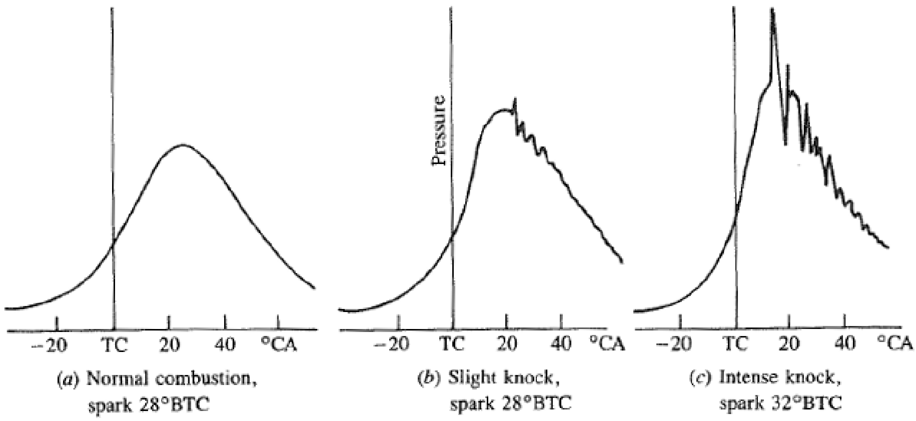

Figure 12 Pressure pikes from knocking events (Heywood, 1988)

Even if an engine can withstand the pressure pikes of lighter knock, it is not desirable to operate the engine in this state, since the abnormal combustion behavior will affect the heat release negatively. Leading to higher component temperatures, and higher NO_x emissions. Furthermore, the higher temperatures inside the cylinder might escalate the knocking into higher amplitudes and a so-called snowball effect is introduced, leading to higher levels of knocking (Heywood, 1988).

2.3.1 Knock tendency factors

Since knocking is linked to the temperature of the end gas zone within the combustion chamber, factors that impact those conditions are of interest, where compression ratio plays an important role. With higher compression ratios, the end pressure before combustion is higher, and therefore temperatures rise as well. However, engines run at a fixed compression ratio and from a control point of view, it is not possible to alter this parameter while the engine is running.

One of the main controllable factors is the point of ignition, referred to as ignition angle or ignition timing. Usually, engines are sold at a fixed engine NO_x output, and by seeking the optimal efficiency the ignition angle is tuned. By advancing the ignition timing, the combustion is phased closer to TDC, increasing the burned gas temperature. This will also pro-long the period at which the end gases are exposed to high temperatures, therefore decreasing the knock margin. It is not only knocking that becomes a problem with higher temperatures, but thermal NO_x formations as well. To meet the set emission levels, combustion temperatures must be kept at certain points, according to the regulations at the location where the engine will be used.

Boost pressure is another engine parameter that can easily be controlled. By controlling how much air is entering the cylinder, the end pressure before the combustion can be altered, and therefore also temperature and knock limits. One obvious and effective way to cool down the gases, is to lower the charge air temperature, but again, the cooling is usually set to a specific point and not used as a controllable parameter. Also, the humidity of the incoming air is a factor that influences the knock sensitivity, since some of the heat released during the combustion will be used to vaporise the water content of the charge air.

Another factor that influences the knocking behavior is the air to fuel ratio. A leaner mixture of air and fuel will combust at a slower speed than a richer one, therefore lowering the risk of knock. This is also controlled by altering boost pressure. The risk with running on an ultra-lean mixture, is if the mixture fails to ignite, so-called misfire. Modern engines, using exhaust gas circulation, can also experience this problem if too much of the inert gases are circulated back into the combustion chamber. Under misfiring conditions, the hydrocarbon emissions will increase, since there are unburned gases that leave the engine (Hiltner & Fiveland, 2006).

2.3.2 Operating window

The operating window, is the area or space in which an engine can operate normally. The window is constrained by factors that are either fixed, or changing over time, such as the ambient pressure and temperature. For a gas engine, the operating area can be visualised by using ignition timing and lambda value as the degrees of freedom, as these are the primary control parameters for a gas engine. In Figure 13, the area in which the engine operates is limited in the upper right side by the turbocharger´s capability to supply the engine with more air when the wastegate, which regulates how much of the exhaust gases are by-passed and not lead through the turbocharger, is fully closed. This is mainly influencing the maximum possible lambda ratio, air to fuel ratio, since the turbocharger operates at its maximum capability when the wastegate is fully closed. In the other end, high exhaust gas temperature limits the engine to run on lower lambda ratios, since the combustion will be later and more of the burned fuel will leave the engine as heat, in other words, lower efficiency. In the upper and lower parts of the figure, knocking combustion and misfiring are the limiting factors, mostly by the ignition timing. In Figure 13, the operating point is set a few timing degrees below the knocking curve, the space in between is the earlier mentioned knock margin. The placing of the point is mainly based on the NO_x tuning of the engine. Higher allowed NO_x levels move the point closer to knocking limits, and wise versa. A smaller knock margin will also result in higher efficiency, because of a faster combustion.

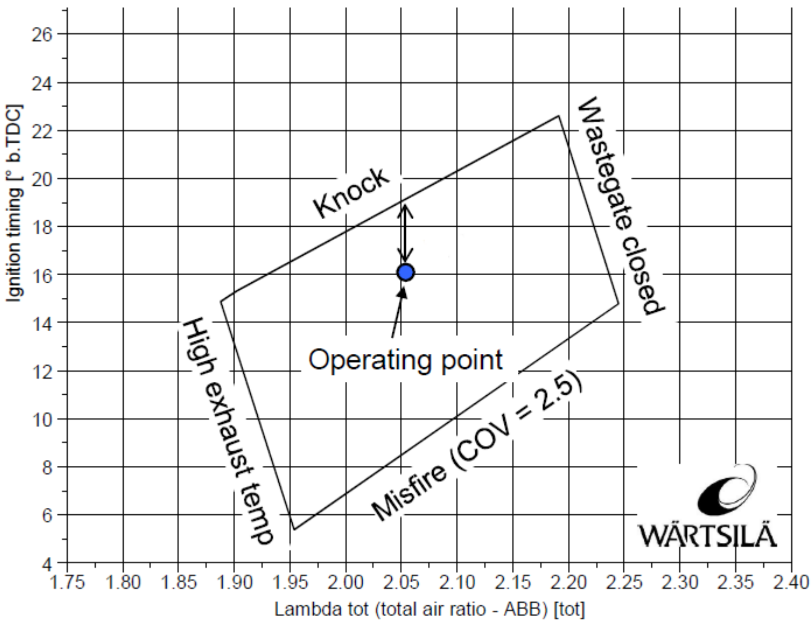

Figure 13 Typical operating window for a Wärtsilä SG engine (Hattar, 2005)

This kind of figure is only valid for a fixed set of parameters, load, methane number and charger air temperature for example. If these values change, the window will move within the timing-lambda diagram. This would require the operating point to move as well, to obtain the same knocking margin. Regarding gas quality and methane number, the knocking line will move downwards with lower MN and upwards with higher MN values. Lower methane numbers might cause the engine to knock, which is countered by a knock detection system, that in first hand tunes the ignition timing closer to the top dead centre, or in the diagram, down, and into the operating window again. The system will afterwards try to tune the timing back to the initial point. However, if the methane number rises, there is currently no control function for the window moving upwards. Which will increase the knock margin at the cost of efficiency (Hattar, 2005).

2.4 Gas quality measurement system at Toftlund Fjernvarme

A few months prior to the start of the thesis, measurements of the incoming gas quality were commenced in a test installation, Toftlund Fjernvarme, located in Denmark. Where incoming gas quality is monitored continuously as their W1834SG engine is running. Gas composition is measured using an MKS Precisive® Gas Analyser, which is connected to the facility's gas piping. Using the measured values, the methane number and heating value are calculated by the system setup. These measurements, along with engine data are logged to an online application and are accessible from any computer or mobile unit. The main objective of this trial, is to test the sensors capability of measuring rapid changes in gas quality, and by evaluating logged data, find a correlation between changing gas composition, engine parameters and knocking levels within the engine.

2.4.1 MKS Precisive® Gas Analyser

The MKS sensor works by a principle where radiation from a broadband light source is partially absorbed by the different gas species present in the sensor cell. Since the light absorption occurs at specific wavelengths and magnitudes, depending on the gas compound and concentration, these can be measured with a spectrometer. In principle, each compound has its own unique absorption spectrum, which can be used to determine the species. Furthermore, the magnitude of the absorbed light, is a function of the number of molecules in the gas. Using this kind of technology, the MKS sensor gives an output in form of a gas composition, which in this case is further used as input for the MN and LHV calculations (MKS Instruments, 2018).

2.4.2 Gas sensor- and communication setup

At Toftlund, the measuring equipment is located next to the gas piping in the engine cell. Incoming gas is lead and controlled by a valve to the MKS sensor, through a piping system with a pressure reducer and flow controller, where pressure is lowered to 0,5 bar and gas flow set to around 0,4 l/min. Since the distance between the sampling point and engine is quite short, the gas has likely entered the engine at the time of a confirmed measurement. However, the gas lag between a confirmed measurement and when the fuel is burned, is dependent on the gas flow to the engine, which is affected by the engine output and energy content of the gas. Measured gas samples are ventilated from the measuring device to the atmosphere, which might seem controversial when trying to improve on hydro carbon emissions. The amounts are anyhow much lower than the blow by emissions that the engine produces, and considering the whole system, the benefits from an engine controller based on real-time gas quality would reduce the overall emissions.

Figure 14 MKS installation with piping, valves, pressure and flow controllers.

The MKS unit is controlled by the engine control system, which activates the sensor and open the gas valves at the sensor piping. Measured data is transmitted from the sensor to the automation system via Modbus communication. Due to different communication protocols between MKS and the rest of the system, the measured gas composition data is first sent to a Programmable Logic Controller (PLC) unit, which decodes the Modbus signal to a 16-bit from 32-bit floating value. The PLC communicates with a COM-10 unit, that runs on the same software as modern Wärtsilä engines, UNIC, which performs the MN and LHV calculations, Figure 15. From here on, the measured values and calculated results are communicated via Modbus, to the Wärtsilä Operating Interface Software, WOIS. Which is run on the control room computer, from where the engine is being monitored.

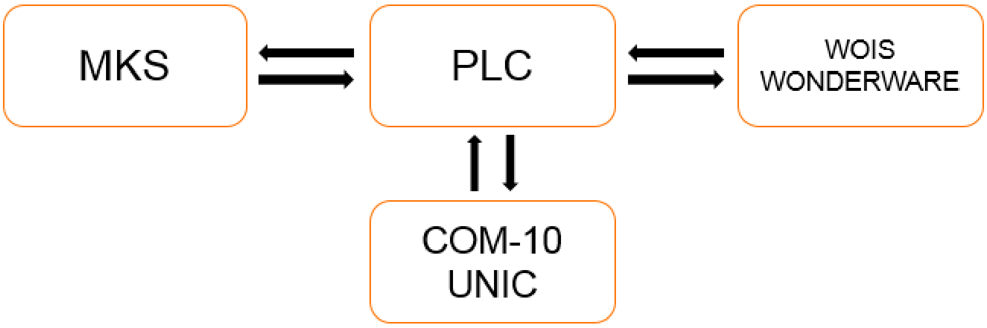

Figure 15 MKS communication setup at Toftlund.

From WOIS, which is the main monitoring system for engine data, these values can be seen in real-time. The same data is also logged to and accessible from an online web interface, called Wonderware. From here, measured values can be observed as the engine is operating, and via this software, the raw data is downloaded for analysis as well.

2.5 MEMS Qs Flonic sensor function and measurement principle

Traditionally, gas analysers measure compositions in gas mixtures. However, MEMS use a different approach to their measurements. The QS Flonic relies on a micro-thermal sensor, based on a complementary metal oxide semiconductor, CMOS. This allows the sensor to measure a mixture for its thermal conductivity, κ, heat capacity, c_p, and from a pressure sensor- and sonic nozzle setup also density, ρ. These parameters are governed by the one-dimensional heat conduction Eq.(16).

$$\frac{c_p}{\kappa}\rho\dot{V}\frac{d}{dx}\Theta = \nabla^2\Theta + \frac{1}{\kappa}Q \tag{16}$$

where $\rho\dot{V}$ is the mass flow across the sensing element, Θ temperature, $\frac{d}{dx}\Theta$ temperature gradient, $\nabla^2\Theta$ Laplace operator on the temperature and Q states the heat input from the hot wire used to determine thermal conductivity. The other physical components in the sensor consists of: a thermopile, critical nozzle, gas reservoir, regulating valve and a hotwire heating element as shown in Figure 16.

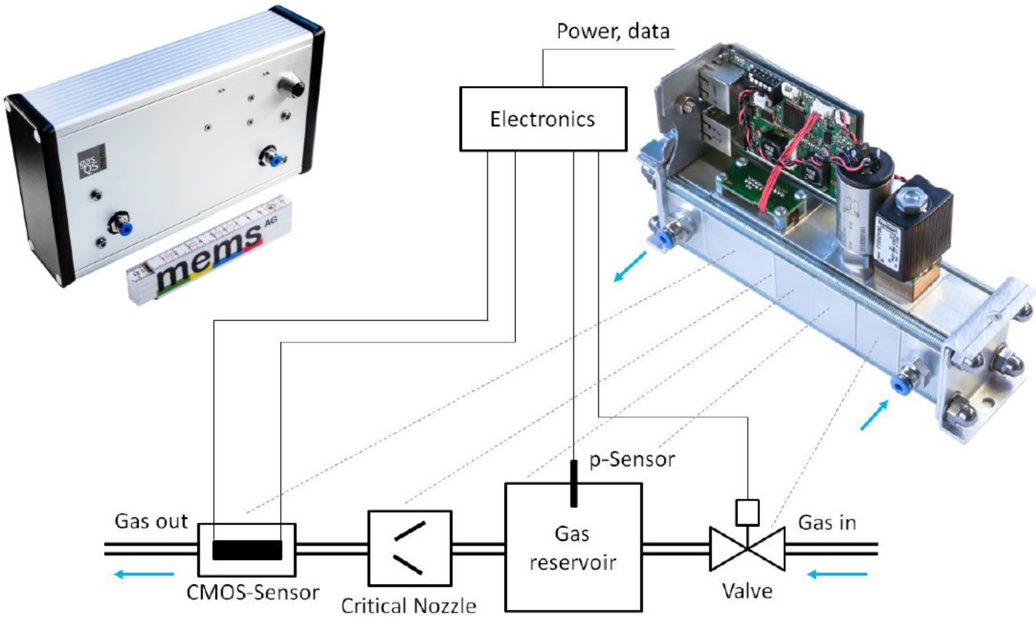

Figure 16 MEMS Qs Flonic gas sensor (Soltic, Biffiger, Prêtre & Kempe, 2016)

One measurement cycle consists of two steps. A magnetic valve is opened to allow the gas to enter a small chamber in front of the critical nozzle. This nozzle is used to create a flow through the sensor, and in that way, also a pressure decay inside the sensor. Which follows an exponential decay law, with the decay time being a function of the molecular mass of the gas. Since molar volume is near identical for most gases, density is inversely proportional to the molecular mass under normal conditions, giving the first parameter

$$\tau \propto \sqrt{M} \tag{17}$$

where τ is the decay time which is caused by the mass flow rate and M is the molar mass of the gas (Zajc & Ryll, 2017). When the pressure before the sonic nozzle equals the back pressure after the sensor chip, flow stops, and the second part of the cycle takes place. Thermal conductivity is derived using a thermopile, located on the CMOS chip. Since mass flow is well defined due to the sonic flow conditions, the third parameter, heat capacity, can be solved from Eq.(16) (Zajc & Ryll, 2017).

These physical parameters $S := f(\kappa, c_p, \rho)$, can be used as input to correlate gas properties, G, including calorific value and methane number. By stating a correlation function $f_{corr}(S)$, describing the relation between the measured parameters and the desired output values, a connection can be found. The correlation schemes are pre-programmed in to the sensor and all the calculations are done within the device. Data is further transferred to a logging program via CAN communication (Soltic, Biffiger, Prêtre & Kempe, 2016).

2.6 Earlier research: "Online gas quality measurement and engine control"

Wärtsilä's internal development project for gas quality measurements was kicked off back in the last months of 2015. During 2016, a master's thesis regarding the subject was written by Jacob Grönroos at Aalto University, where the practical work was done within the development project. The focus of his research was placed on newer and faster gas sensing technologies, compared to traditional gas chromatographs. Mainly by testing the MKS Precisive gas analyser, which was new for Wärtsilä at that time. Apart from the tests with the MKS, he also proposed a communication setup to the engine control system, and showed that the control system can calculate MN according to the new model. As one of the results he listed a few possible ways on how to make an engine control function based on methane number, by for example changing engine timing and boost pressure. Finally, a simulation with a real time engine load derating function was conducted, to prove that a control application with MKS readings is possible. In the conclusions, the MKS sensor was found to be accurate enough for the intended purpose.

As recommendations for future development (Grönroos, 2016) stated, "Engine derating avoidance by changing charge air and ignition timing" and "Engine optimisation for changing LHV and MN" as the most important ones.

3 MATERIAL AND METHODS

This chapter will explain the work process and different steps of the Thesis. In the beginning of the project a decision to divide it into four different topics was made, these will be presented in detail here.

3.1 Follow-up of Toftlund Fjernvarme measurements

Regarding the communication setup, some small updates were finished during a visit to the site. Mainly considering the channels that the MKS uses to transmit data and how the software's handle them as inputs. As earlier mentioned, the output from the sensor is a total gas composition. The sensor measures hydrocarbons and carbon dioxide contents of the gas and balances the remaining part with nitrogen up to 100%. In Table 2 the channels that are being used for the communication can be seen. Channel 6, that transmits the pentane reading, reports the two isomers lumped together, since the MKS cannot differentiate them. A bug in how the UNIC software handled them as inputs was discovered, more specifically how the signal was treated as ratios of the two isomers, i-pentane and n-pentane. For some reason the channel value was not divided, but only separated to two different inputs. Meaning that the total amount of pentane present in the calculation doubled. The problem was solved by making the ratio a changeable parameter in the software, which can be altered using a UNITool software. The values were set according to what is normally an average in the distributed gas, 80% n- and 20% i-Pentane, these are however quite small quantities and their knock behaviour are very similar.

Table 2. MKS MODBUS output registers at Toftlund

EC_General_01.Value	Methane reading %
EC_General_02.Value	Ethane reading %
EC_General_03.Value	Propane reading %
EC_General_04.Value	i-Butane reading %
EC_General_05.Value	n-Butane reading %

EC_General_06.Value	i-Pentane and n-Pentane reading %
EC_General_07.Value	Carbon dioxide reading %
EC_General_08.Value	Nitrogen balance reading %

3.1.1 Smart NO_x sensor

In addition to the earlier mentioned gas quality measurements, the installation is also equipped with a Siemens Smart NO_x sensor. Which measures nitrogen oxide and oxygen contents of the exhaust gas, as the engine is running. With this sensor, the purpose is to see how the NO_x emissions change in relation to gas quality. It is already known that the emissions are linked to end gas temperatures inside the cylinder, and therefore also to the efficiency of the engine. The real objective is, however, to study at what rate, and how much the NO_x formations are affected. With this data, it could also be possible to deduct how the engine would behave if adjusted to the same NO_x levels over the whole MN span.

However, some setbacks were encountered with the NO_x measurements. After the tests had been going on for a few months with this setup, the sensor failed. It was returning false values, if any at all, from time to time. During the mentioned site visit it was replaced to a new one, with limited success. It was concluded that a possible root cause for the failure could be thermal overheating of the wiring harness. Due to the exhaust gas heat recovery system that the installation is using, the piping is heavily insulated for maximal effect.

Figure 17 Smart NO_x sensor placement (Photo: D Högberg)

As the sensor is placed inside the exhaust pipe, most of the wiring is lead through the insulation material, therefore it is constantly exposed to high temperature, with very poor cooling from the ambient air, Figure 17. This is believed to be the cause of the fouling sensor. An idea to construct a funnel around the wiring for better cooling was proposed and approved by the plant owner.

3.1.2 Performance analysis based on methane number

The focus of this analysis was put on events where rapid variations in MN could be seen, as well as other interesting behaviours. In practice, the monitoring was done on a daily and weekly basis by following the operation of the engine through Wonderware Online. As a special case study, an incident where the MN dropped from around 90 to 70 in about 45 minutes was chosen. In this study, the calculations made, were based on the performance- and gas composition data acquired from Toftlund as a five-minute average (Appendix 1).

Here it could be observed that the way the engine is tuned, efficiency along with knocking values decreases when the incoming gas is changing from a high methane number to a gas with higher contents of ethane and propane. At this point the NO_x sensor was not reporting any values anymore, therefore they could not be compared here. However, from a similar calculation created by Jenny Jansson at Energy Solutions, NO_x values were also shown to decrease with the lower efficiency, which is expected.

3.2 50SG Methane number-based control tests

Apart from the Online gas quality measurements project, the automation department was also investigating in how to utilise methane number and gas quality for fuel transfers between ethane, propane and natural gas, for a low methane number version of the 50SG engine. On their behalf a decision to test engine tuning with the MKS readings as input was made. These tests were decided to include into this thesis as well, as they fall within the scope of the project. The practical testing was made together with experts from different departments within Wärtsilä, on the 6L50SG engine located at the engine laboratory in Bermeo, Spain, over the course of one week.

3.2.1 Communication and sensor setup

The communication between the connected systems in Bermeo was arranged in a similar fashion to the setup in Toftlund, accordingly to Figure 18.

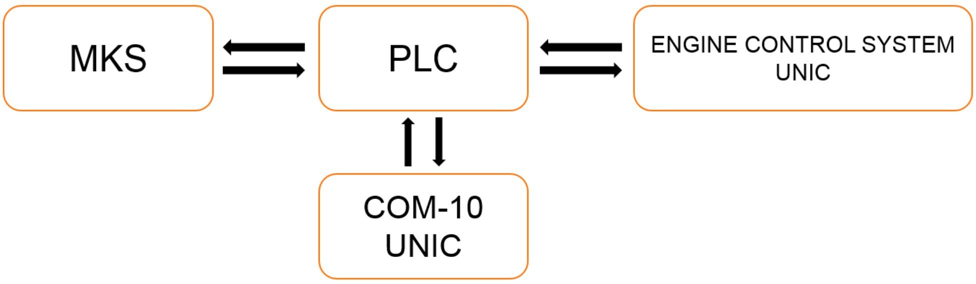

Figure 18 MKS communication at Bermeo engine laboratory

Where the measured gas composition and a calculated LHV value is transferred from the MKS to the PLC. Some modification of the signals is done within the PLC, before it is sent to the COM-10 where the methane number calculation is performed. The PLC retrieves the data from the COM-10 and sends it forward to the engine control system, where the idea is to use it as an input for engine parameter tuning. The Modbus list, stating which compositions are sent over which channels, is however slightly different compared to the one in Toftlund. This is because the current recipe is calibrated to measure higher ranges of ethane and propane, and therefore some of the lumped compositions differ from the old recipe. For this reason, it was decided to move the rationing part of the channels, from the COM-10, to the PLC. In order to have a standardised UNIC software in the future. With the new setup, all the modification, normalisation and dividing of channels into different isomers of a composition is done within the PLC, and as such, the COM-10 will only handle one isomer of one composition per channel.

Table 4. MKS MODBUS output registers at Bermeo

EC_General_01.Value	Methane reading %
EC_General_02.Value	Ethane reading %
EC_General_03.Value	Propane reading %
EC_General_04.Value	i-Butane reading %
EC_General_05.Value	n-Butane and n-Pentane reading %
EC_General_06.Value	i-Pentane, neo-Pentane and n-Hexane reading %
EC_General_07.Value	Carbon dioxide reading %
EC_General_08.Value	Nitrogen balance reading %

By studying the gas chromatograph readings for the incoming natural gas, channel five is divided into 90% n-Butane and 10% n-Pentane. Likewise, channel 6 is divided into 100% i-Pentane, leaving neo-Pentane and n-Hexane at 0%, simply because they are not shown to be present in the gas supplied to engine laboratory. These rationings were as earlier described included in the PLC unit. In the engine cell, the sensor itself was connected prior to the arrival at Bermeo and placed next to the engine gas ramp. The sampling point is placed 12 meters away from the first engine cylinder inlet, from where it is lead to the MKS sensor in a four-meter-long pipe. In addition, the flow can only be regulated by a hand operated shut-off valve, with no pressure- or flow regulator, which would be very useful, since the MKS is somewhat sensitive to pressure pikes. The knowledge about the flow thru the sensor is also valuable, regarding gas lag between the sensor and the engine.

3.2.2 Engine mapping

The parameters for engine tuning are usually determined by so called maps. A map consists of two input parameters that function as x and y axes in a diagram. The controlled output will then be a function of these two inputs. In practice the engine control system will use these maps to determine what values to give as output to the engine. For these tests an existing, not normally in use, application for engine tuning based on calorific value of incoming gas was used. With the input on the y axis changed from calorific value to methane number. From the mentioned application, two different maps were used for controlling the engine during the transfers between different gases: an ignition-timing map and a boost-pressure map. As input values for the control, methane number and engine load, defined as break mean effective pressure, were used. For the different pure gases, methane numbers were 35 for propane, 51 for ethane and 75 for natural gas. In the maps these values were set as specific points, and as the methane number or load (electrical output) changes either down or up, the control function will interpolate between the nearest values.

Ignition timing map, Low calorific [CCM-20 A1]

Ignition timing

Calorific value (kJ/kg)	0	2200	4400	5500	6600	11000	16500	22000
3500	10.0	14.0	15.0	15.0	15.0	11.0	11.0	11.0
4000	10.0	14.0	15.0	15.0	15.0	11.0	11.0	11.0
5100	10.0	15.0	16.0	18.0	18.0	15.0	13.0	10.0
6000	10.0	15.0	16.0	18.0	18.0	15.0	13.0	10.0
8000	12.0	18.0	20.0	20.0	20.0	20.0	19.0	19.0
9000	12.0	18.0	20.0	20.0	20.0	20.0	19.0	19.0
10000	12.0	18.0	20.0	20.0	20.0	20.0	19.0	19.0
10000	12.0	18.0	20.0	20.0	20.0	20.0	19.0	19.0

Figure 19 Ignition timing map with MN with a factor of 100 and BMEP in mbar as inputs.

EWG CA press ref map, Gas, Low calorific [IOM-10 TC]

EWG CA press ref	0	2200	3300	4400	6600	8000	9000	11000	13000	15000	16500	18000	19800	21000	22000	24200
3500	0	130	290	450	805	1040	1241	1644	2120	2671	3093	3515	3515	3515	3515	3515
4000	0	130	290	450	805	1040	1241	1644	2120	2671	3093	3515	3515	3305	3502	3943
5100	0	50	171	295	750	900	1031	1440	1850	2300	2600	2692	3056	3305	3502	3943
6000	0	50	171	295	750	900	1031	1440	1850	2300	2600	2692	3056	3305	3502	3943
8000	0	85	209	331	650	876	1046	1379	1756	2133	2411	2723	3117	3358	3616	4130
9000	0	85	209	331	650	876	1046	1379	1756	2133	2411	2723	3117	3358	3616	4130
10000	0	85	209	331	650	876	1046	1379	1756	2133	2411	2723	3117	3358	3616	4130
10000	0	85	209	331	650	876	1046	1379	1756	2133	2411	2723	3117	3358	3616	4130

Figure 20 Boost pressure map with MN with a factor of 100 and BMEP in mbar as inputs.

The functionality of the tuning was to reduce the ignition timing and increase boost pressure when the methane number would decrease, and vice versa. In basic, the engine is tuned according to the ignitability of the gas (MN), where natural gas parameters will have an earlier ignition timing and lower A/F ratio compared to Ethane and Propane. Even if the engine that was tested is running on relatively low compression ratio, to be able to handle low methane number gases, the tuning needs to be correct to operate the engine, especially on higher loads. If there would be any issues with the control, leading to wrong ignition timing, the engine could possibly either knock or misfire due to the large variety in MN. The exact values for timing and boost pressure for the specific gases were taken from performance tests that had been performed on the engine earlier. In practice this means that the maps do not consider changes in natural gas quality above MN 75, since the supplied gas at the laboratory had a methane number at around 75. So therefore, any tests with higher methane number could not be performed. However, as they do interpolate between values and the switches between gas types, and as the transfers between gases are completed in a slow, ramping manner, it can be seen as a typical gas quality change. Noticeable aspects in Figures 19 and 20 are that the MN has a factor of 100, BMEP and boost pressure values are in mbar and ignition timing is expressed as crank angle degrees before TDC.

3.2.3 Test program for gas transfers

Since these tests were the first ones performed with a methane number-based engine control the focus was primarily placed on the functionality of the control and the communication between all the different components present in the system. With the whole chain of communication working, the target was to enable transfers between natural gas and the lower methane number associated gases, propane and ethane at the maximum possible load for each. Among initial testing with the application enabled and other parameter tunings, the more interesting points run that are covered in this thesis are listed below.

1. First start with application enabled. The first transfer was performed from natural gas, to mixing in 20% propane, and after running a while at 80% natural gas, 20% propane, switching back to pure natural gas. This was done at an engine load of 30% out of maximum output
2. Transfer from NG to pure propane and back to NG at 30% output
3. Transfer from NG to pure propane and back to NG at 50% engine load, shutdown from heavy knock
4. Transfer from NG to pure propane and back to NG at 50% engine load
5. Transfer from NG to pure propane and back to NG at 70% engine load
6. Transfer from NG to pure ethane and back to NG at 70% engine load
7. Transfer from NG to pure ethane and back to NG at 100% engine load
8. Immediate, fast transfer from NG to ethane at 30% out of maximum engine output

Engine load and maximum output is defined as percentages of what the highest allowed power output is when the engine is operating on natural gas. The results from these test points are covered in the results chapter, along with other findings and problems related to the control functions.

3.3 Testing and evaluation of MEMS QS Flonic sensor

As earlier described, an MKS Precisive sensor has been tested within Wärtsilä and installed to the mentioned powerplant in Toftlund. In this part of the project a sensor with a different technology was tested, the MEMS QS Flonic sensor. The purpose of this study, was to determine what types of measures it can handle, where it can be used, and if this device could be used for quality measurements regarding engine control. Initial tests with the new sensor, alongside with the MKS for comparison were carried out at Wärtsilä's fuel laboratory. For long term testing, the MEMS sensor is to be placed in the engine laboratory, measuring gas properties continuously as the laboratory engines are running. Evaluations of the test results were carried out all along the way.

3.3.1 Fuel laboratory tests

Initial testing of the sensor's function and usability was done in Wärtsilä's fuel laboratory in Vaasa together with Andreas Kempe from MEMS AG and in-house personnel. For these measurements, a test plan was made with different compositions that were going to be measured with the sensor. Using a comprehensive list of gas compositions and corresponding methane numbers, MEMS prepared a suitable correlation for WMN and LHV. The testing was done over the course of two full days. A mixing station was used to achieve the desired compositions, using differential pressures to determine right amounts of pure gases (Appendix 2). In addition, the MKS Precisive was used to log data for reference, and result comparison.

Measurements are setup in a way that the MEMS and MKS sensor are placed in series, with the gas entering the MEMS first. In this way corresponding measurements from both analysers are achieved. The period for measuring is set to around 20 minutes, resulting in about 35 MEMS readings for each composition. After each test, a new composition is mixed in the mixing station and the system is purged out from old gases

Logging of the measurements were done with a MEMS implementation of a program called LABView. Through this software the sensor can be controlled manually, and measurements started and stopped. Analysed data that the MEMS QS Flonic returns as output is: LHV (kWh/m3), Wobbe Index (kWh/m3), WMN, AVL MN, Density (kg/m3). In addition to these, there are also some sensor specific parameters regarding the nozzle- and flow saved into the same file. The logging program also saves the raw data from the measurements, which gives the opportunity to “tune” the sensor afterwards. With the access to the direct signals, better correlation schemes can be fitted for example to the Wärtsilä methane number, which probably is the biggest challenge with the MEMS sensor.

The results from the initial testing is gathered together with corresponding results from the MKS. A comparison with the both sensors and the actual parameters of the mixed gas is made and will be presented in the next chapter.

3.3.2 Engine laboratory installation and testing

For long term testing of the sensor’s robustness and drifting, it was decided to be installed in the Wärtsilä City engine laboratory. According to the plan, the sensor will be placed outside, next to the LNG tanks and set up to communicate with the facility’s automation system. The sensor would be left to measure gas composition and be monitored by the engine lab personnel for about four months, where after further actions would be decided, based upon the results of the tests.

To begin with, an initial test was done together with Guy Hägglund, chief automation engineer at the lab to test the communication and see if the sensor can be fitted to the lab system. Since the current version of the sensor communicates over CAN protocol, a CAN to Modbus RTU converter was used to connect it to a desktop computer via ethernet. Connection towards the sensor was successful in the sense that a line of communication was open, however, the sensor was not returning any values when requested to. Considering that the sensor needs to be pressurised to perform measurements, it was tested with compressed air, with no further success. According to Hägglund, the problem was related to the conversion between CAN and Modbus communication. MEMS AG was contacted about the problem and offered to supply a separate CAN to Modbus converter of a different make, configured and tested by them.

At this time, the sensor being tested was a rented Qs Flonic V1, with a rent to purchase contract. As MEMS were currently at the stage of launching the newer version of the sensor, an agreement to switch the rented V1 to a purchase of the V2 was made. As the newer version is an ATEX certified sensor, there would be no need of an extra ATEX approved casing when installing the sensor at the gas field, which solved a major problem. The newer version also uses Modbus RTU communication, so the need for a converter was also eliminated.

3.4 Reference gas and correction factors

This part of the thesis work is primarily a theoretical study on engine performance data from Wärtsilä´s laboratory engines. The basic idea of a reference gas coefficient is that whatever gas you operate your engine on at the factory test run, efficiency and emissions could be estimated for another type of gas by using compensating factors, if operating conditions and tuning is alike. A new reference gas, G-LNG was also proposed within a joint project between Wärtsilä and other parties in the industry. For instance, an engine maker can at their factory test use a methane number 75 gas, and by applying the mentioned correction factors, accurate values for emission and electrical efficiency can be provided to the customer, who will operate with a methane number 90 gas.

As seen in Toftlund, efficiency and NO_x emissions variations are significant in relation to the gas quality. This is however quite an extreme case, but it does illustrate the need. The benefits of the correction factors for gas quality are many. For instance, the possibility to more accurately estimate the impact of operating on different gases for customers, especially as many ship operators bunker LNG at different locations over the world. In the future, engines could be tested and sold according to one gas, with correction factors for MN variations. If the new reference gas would be implemented as a new standard, and widely accepted, it would bring transparency to the competition between engine makers as everyone would be required to test their engine according to the standard. This is however both good and bad, as it might be beneficial for some to show their performance according to a standard, and not for others.

As input for the study, W31SG performance data and corresponding gas composition was used to make the numerical calculation. The selected points were taken from earlier load derating tests done at the Bermeo- and Vaasa city laboratory. When performing the experiments to determine the load derating points, engines are operated with fixed tuning over a span of different methane numbers to check where the engine starts to knock. Lowering of the methane number is done by mixing in propane into the supplied LNG or pipeline gas. It was decided that these results would be suitable as input for this part, and that no separate testing would be needed.

3.4.1 G-LNG reference gas

For the moment being, there are a couple of different test gases defined in the EN-437 standard, most of which are pure methane diluted with either nitrogen or hydrogen. There is however one essential problem with these. Their similarities with any real-world existing fuel is next to none. Only one of these gases seemed to be comparable with market gases. This test gas is named G_R, and achieved by adding 13% ethane into methane, giving it somewhat similar properties to what a typical LNG could have. However, it doesn't quite reassemble the typical properties of a gas containing propane (Nicotra, 2012).

And with the knowledge about what the future LNG market will look like, a suitable composition for the, G-LNG, was nominated by the project core team. One of the criteria for the gas was to ensure that the blending of the gas will not be too expensive and complicated, therefore it was decided that the mixture should not contain hydrocarbons above propane. The gas composition should also be close to what is seen as the optimum performance point of engines in general, to prevent over conservative designs. Lastly and most importantly, the reference gas should resemble the gases that are available in the market. What they studied, was the global average- and most common mixture of LNG that is present on the recent market.

Table 4. G-LNG compared to global average and most common LNG (Koot, Future LNG Quality Study, 2018)

	Global Average (Weigt & Norm)	**Most Common** (Qatar Lean)	**Proposed** (G-LNG)
Methane	92.9	93.3	92.5
Ethane	5.2	6.3	6.0
Propane	1.2	0.1	1.5
iso-Butane	0.2	0.0	0.0
n-Butane	0.2	0.0	0.0
C4+	0.0	0.0	0.0
Nitrogen	0.2	0.4	0.0
PKI	79	88.0	82.0
AVL	78.9	84.00	79.9
Wartsila MN	78	86.00	80
Gas density (kg/m3)	0.73	0.72	0.73
LNG density (kg/m3)	445	439	445
HHV (HHV. MJ/kg)	54.8	54.8	55

The proposed G-LNG that can be seen from Table 4 correlates very well with both the global average-, as well as the most common, Qatar Lean LNG. Another advantage with having only hydro carbons up to propane, is that all the MN calculation methods align with each other. The actual value is 80 on the WMN scale and is also something that is considered a middle point, or a number to which most engines are optimised to (Koot, Reference gas proposal - G-LNG, 2018).

3.4.2 Efficiency, NO_x and THC correction factors

Using the test points described in the beginning of this chapter, a comparison between consecutive tests is performed and plotted as electrical efficiency in regard to methane number. As input for the emission factors, measured values are used. For the MN and LHV calculation, the measured, natural gas composition and re-calculated, blended gas composition is utilised. The different tests are plotted as their own series in the same diagrams, and the idea is to derive one factor for each test series and afterwards calculate a mean factor and study how well it would fit overall. The actual work is done with Microsoft Excel's inbuilt trendline function and normal mean value calculations.

Eq.(17) expresses how a linear function would look like for correcting the electrical efficiency according to methane number.

$$efficiency_{corr} = efficiency_{ref} + \left(MN_{ref} - MN_{new}\right) . C_{eff} \qquad (17)$$

$efficiency_{corr}$ = Corrected electrical efficiency

$efficiency_{ref}$ = Measured reference efficiency

MN_{ref} = Reference methane number

MN_{new} = The new methane number which the engine will run at

C_{eff} = Correcting factor

4 RESULTS

This chapter will present the results and findings that were discovered during the tests, calculations and overall work process. The subchapters are ordered in the same way that they were presented in the previous chapter.

4.1 Toftlund 18V34SG case

From the data acquired at Toftlund (Appendix 1) the efficiency is calculated according to Eq.(11), and is shown to increase with lower methane numbers. Figure 15 shows the change rate in efficiency versus MN, where numerical values are hidden for confidentiality reasons. The actual difference is 1.5 %-units higher efficiency per 10 MN units.

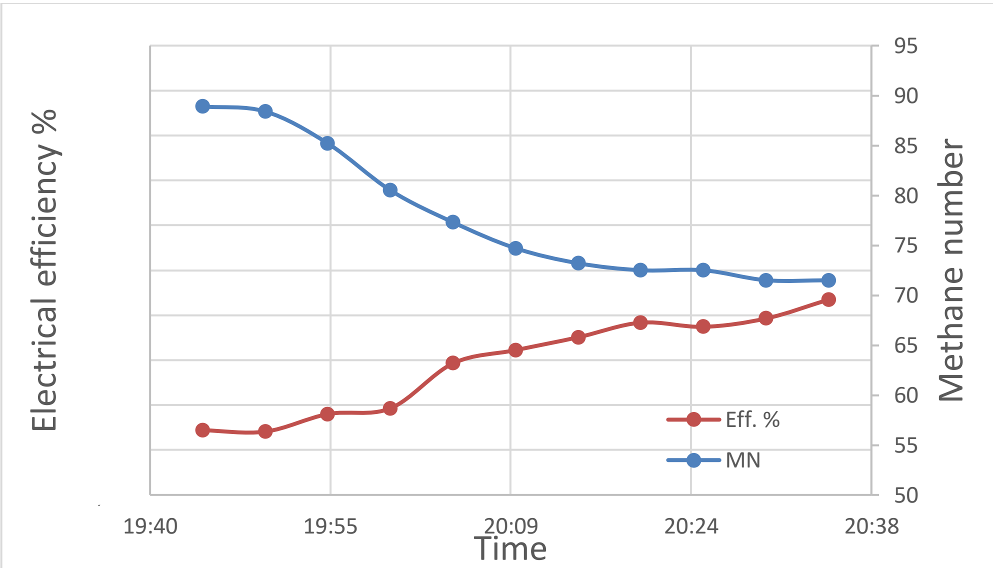

Figure 21 Efficiency and MN changes at Toflund Fjernvarme 21.3.2018. (Appendix 1)

The change in methane number seen in Figure 21, is due to the contents changing in the incoming natural gas, in form of ethane -6.7 %-units, ethane +2.8%-units, propane +2.2%-units and some minor increases i- and n-butane and pentane (Appendix 1). Some small amounts of inert gases, in form of nitrogen is present in the gas at Toftlund, they will increase the MN, but as the quantity is very small and so are the variations, they do not have any bigger impact for this study.

4.1.1 Toftlund site updates

The updates that were carried out during the site visit was for the larger part successful. Updates to the UNIC calculation for the MN were carried out and as a result it is now showing correct values. The failure of the Smart NO_x sensor was fixed by changing the sensor itself. As a result, it gives measurements, but not any reliable values. Overall the gas measurements with the MKS sensor and communication between the different system works reliably, as well as the remote monitoring with Wonderware Online.

4.2 50SG Methane number-based control tests

4.2.1 20% Propane transfer on 30% load, first start with application enabled

As a first functionality test of the methane number controller, a transfer was done at 30% engine load and with the gas valve positions set at 80% natural gas and 20% propane, which gave an MN deviation from 75 to 46, and back to 75. During the transfer, the controller reacted as it should to the changing gas quality, without disturbing the combustion. No knocking or misfiring was observed either. However, the engine was configured with a quite low compression ratio of 9.5 and since it was not loaded that much, there should not be any problems when switching over at this point, regarding knocking.

4.2.2 Propane transfer on 30% load

Secondly, a transfer between natural gas and pure propane was made at engine load of 30% out of maximum output, with a methane number changing from 75 down to 36 in about 60 seconds. As a feedback of how well the engine was running, IMEP trends for all cylinders, numbered A1 to A6 was used. IMEP is described in the theory chapter as indicated mean pressure and in practice it increases with engine output. For this project it is interesting to examine the differences in actual values when the engine is operating in steady state on different types of gases, this is related to how well the maps are tuned for the different methane numbers. But it is also used to investigate how each cylinder reacts to the methane number-based control function. Some disturbances can be seen during the shifting between gases and parameters change, but in steady state operation the trends look normal, Figure 22. No knocking problems were observed during this transfer either.

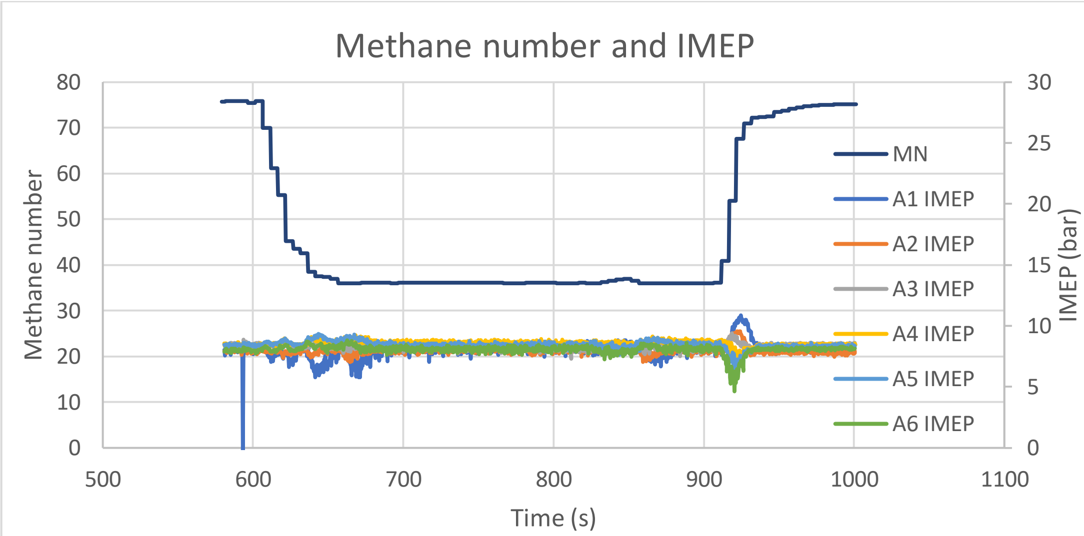

Figure 22 IMEP of all cylinders during transfer from NG to Propane and back.

4.2.3 Propane transfer on 50% load, shutdown from heavy knock

The next point was a transfer to propane and back to natural gas on 50% engine load. During the ramping back to natural gas the engine shut down from heavy knocking, probably due to a too fast switch and therefore the MKS sensor did not have time to react to the sudden jump in methane number. Most probably, the engine was operating on natural gas with propane parameters for a moment, which lead to poor combustion on some cylinders, increasing the work load for others, which can be seen in Figure 23. Since some cylinders are working harder, they are the ones starting to knock and eventually causing the shutdown.

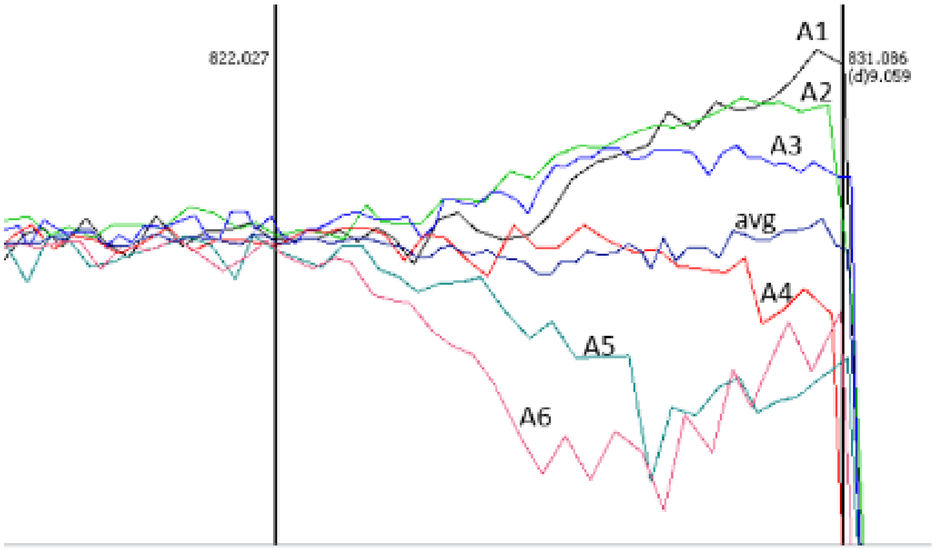

Figure 23 IMEP (bar) trends for all six cylinders labelled A1 to A6 during the shutdown.

In Figure 23 it can also be observed that the lowest lines are represented by the cylinders closest to the gas pipe inlet on the engine. These cylinders are also the ones starting to misfire first, strengthening the theory of natural gas present in the engine before the sensor and control has reacted to the change.

4.2.4 Propane transfer on 50% load

After some tuning of the parameter in the software, another attempt to transfer between gases at 50% load was made. This time with a slower ramp rate, about 5 minutes from natural gas to pure propane. The transfer was successful and repeated once, also successfully. However, the IMEP trends showed similarities to the previous attempt when going back to a higher methane number, the engine was not knocking though.

The opposite trend could also be seen when going down in methane number, where the cylinders further away from the gas inlet would start to misfire slightly, and the ones closer to the incoming gas would go higher in IMEP. This confirms that there is some flow that is not homogeneously mixed when entering the engine. This can be seen in Figure 24 which shows the methane number, IMEP for cylinder A1, furthest away from the engines gas inlet and IMEP for cylinder A6, which is closest to the incoming gas pipe.

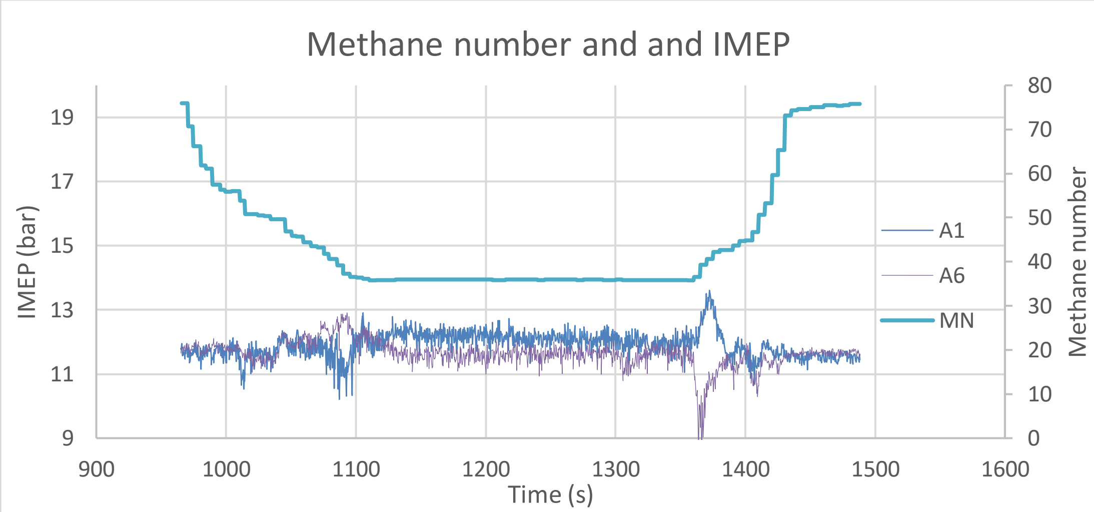

Figure 24 MN and IMEP for cylinders A1 and A6

4.2.5 Propane transfer on 70% load

The main goal of these tests was as earlier said, to enable transfers between different gases at the maximum rated power. For pure propane, the output is set at 70% of the maximum power allowed when running on natural gas. Also, during this test point, the switch between natural gas and propane was done in a relatively slow manner to avoid sudden peaks or drops in methane number. This transfer succeeded without any problems, even though the IMEP trends show some small deviations.

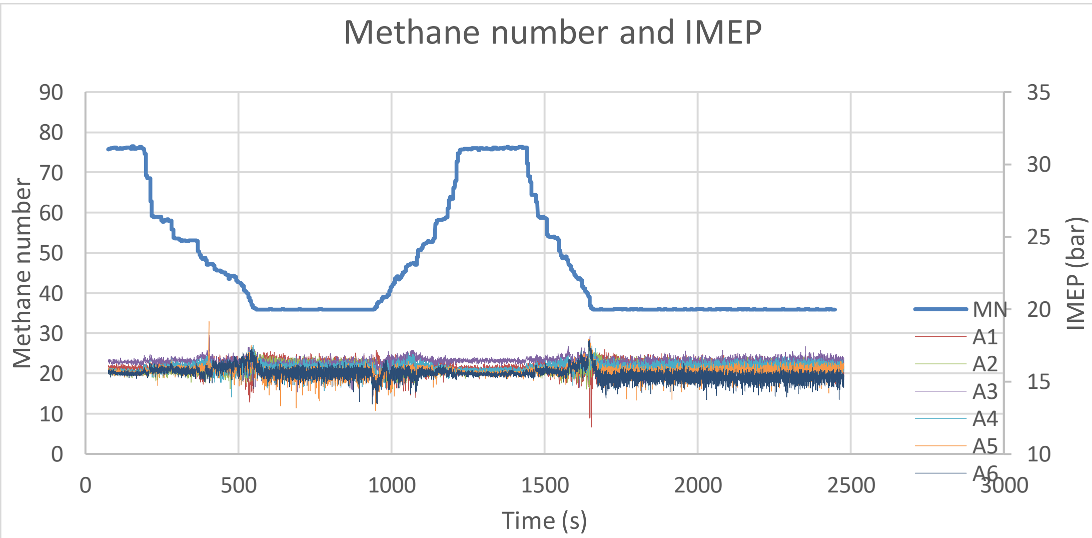

Figure 25 MN and IMEP for transfer between NG and Propane at 70% load.

From Figure 25 it can be observed that the engine was running well on all cylinders during the transfer. All and all the control function enables transfers on full rated output for Propane. However, some tuning would be required to get to the same level of stability as on natural gas, which can be seen from the fluctuations in IMEP during steady state operation at full load on the two different gases.

4.2.6 Ethane transfer on 70% load

As there was some time and possibility to run tests on ethane at the engine laboratory, a few transfers were tried to further test the control function. Since ethane is more knock resistant than propane, it is possible to operate at maximum rated output with the current setup of the 50SG engine. The first point was although done at 70% engine load, which went by with ease. In a way this was expected, since the methane number changes less, only about 25 units.

4.2.7 Ethane transfer on 100% load

As with the 70% load tests, the full load transfer went very well. IMEP trends showed little to no deviation during the transfer and remained stable over the whole period, going both up and down in Methane number. At this load, the engine was running well on all cylinders, which in a way proves the accuracy of the MKS sensor, since the mapping of boost and ignition is based on its readings.

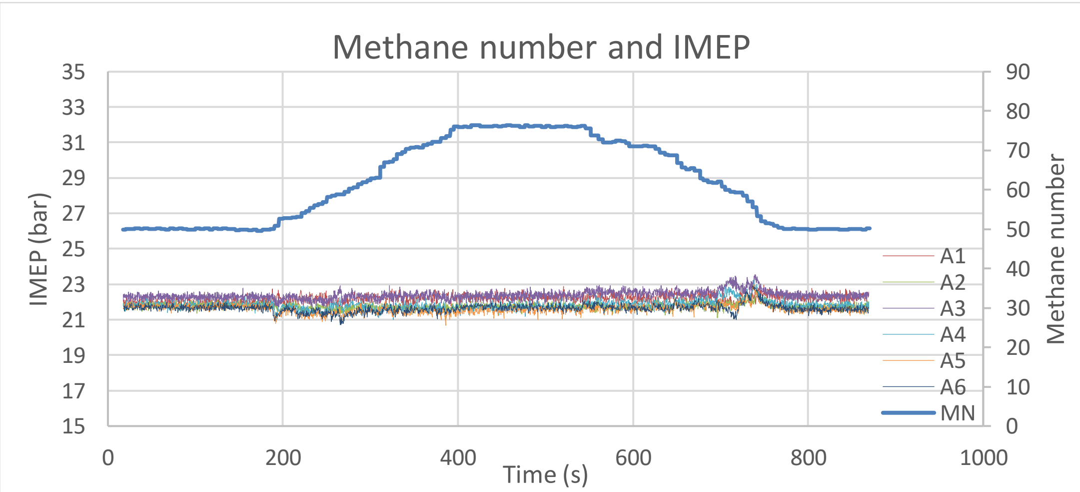

Figure 26 MN and IMEP for transfer between NG and Ethane at 100% load.

4.2.8 Other findings

During the start-up of the engine on the second day of testing, it was found that the MKS showed some incorrect values. The sensor gave an output of methane number 48, even though the engine was stopped on natural gas the day before. After some minutes of fluctuating, the readings finally stabilised at MN 75. Because of this problem, the first start of the engine failed. It was thought that some propane could still have been present in the pipe, which would have condensated during the night, eventually causing the problem.

Also, during the transfers from lower methane number gases back to natural gas, a small bump was observed in the methane number readings before the actual increase was measured. This might be caused by a pressure pike inside the gas pipe as the different valves in the system are actuated. The MKS is quite sensitive to pressure deviations and this sort of problem could easily have been solved by using a pressure regulator.

One of the main concerns with these measurements and the functionality of the control is the lag between measurements and the gas entering the cylinders. From these tests it was difficult to discern any type of lag between these two. However, the lag is related to the piping length from the sampling point to the sensor and engine and related to the current gas flow to the engine. This is something that should be evaluated further and considered when developing a real application. As the rate at which the methane number was changing during these tests was quite slow it did not cause any trouble, except for the "fast" 50% load transfer on propane.

4.3 MEMS QS Flonic gas sensor initial test results

The initial testing revealed a lot about the capabilities of the sensor that was tested. Both practical, and measurement related issues were encountered. As the version that was tested used CAN communication protocol, there was some connectivity issues from time to time during the testing. Another problem was the time to blend the different mixtures in the mixing station, which decreased the number of blends that was able to measure. Aside from the communication issues with the CAN to USB converter the device seemed quite easy to use, and it would not require much attention if left to measure continuously for a longer time.

Initially, the plan was to use a gas chromatograph that would measure the composition exactly as reference. However, there was not enough piping and connecting pieces to have it connected. Due to time shortage, running out of ethane and other smaller problems, only half of the planned compositions were carried out.

4.3.1 Methane number

In Figure 27, the methane number measurement of one of the tested compositions is plotted. For this composition the MEMS reported a MN about 2 units higher than the reference value. The measurements are anyhow quite stable, and the different points do not deviate very much from each other. This proves that the measuring part of the sensor is reliable. In the end, where the values have flatlined, the gas pressure has been cut off and the sensor will return the latest value until the measurement has been stopped manually.

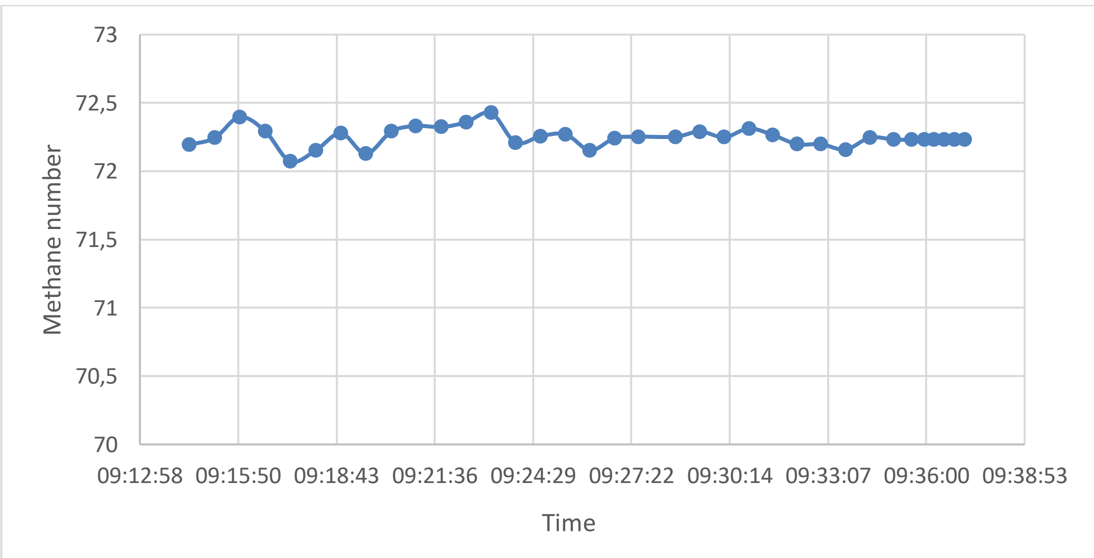

Figure 27 Measured methane number over time for test id N8, with reference MN 70.

Looking at all the test compositions plotted into a diagram with the mixed values on the x-axis and measured methane numbers on the y-axis, more variation between the two can be seen. Figure 28 shows the deviation between the MEMS and MKS measured methane numbers compared to the linear, actual value line. This graph shows that there are uncertainties in the measurements, both with the MEMS and with MKS as well.

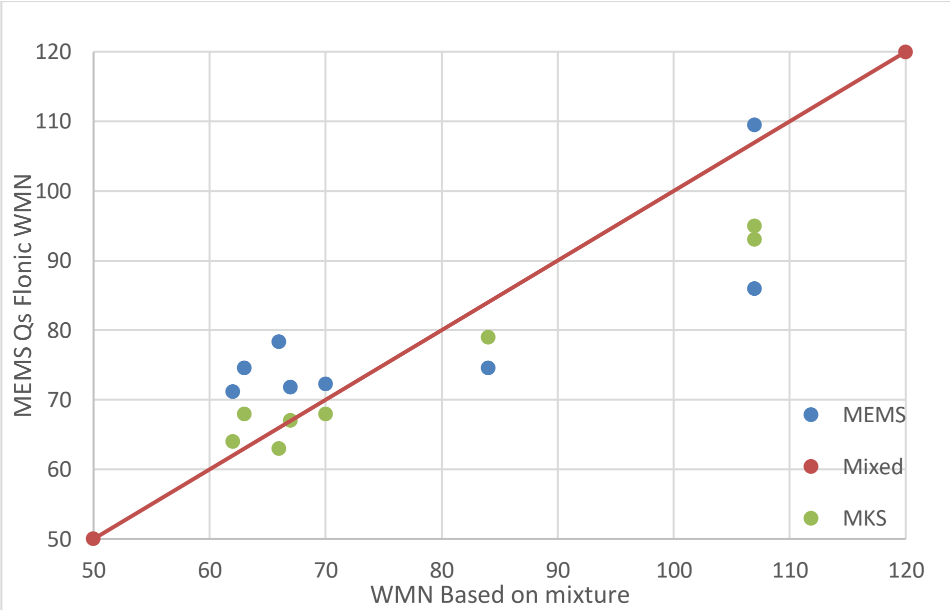

Figure 28 MEMS and MKS measured MN compared to actual values.

A few points do correlate very well with both the sensors and the actual value, some only with MKS and one of the points where only MEMS is close to the linear line. The average error for the MKS measurements were 5.4 units of MN and for the MEMS sensor the average error was 9.1 units.

4.3.2 Lower heating value

Measurements of energy content in the gases were more consistent than those of MN. Figure 29 shows that both the MKS and MEMS correlates very well with the LHV that was calculated based on the mixed composition. At the same time, it shows that the MEMS sensor is very well capable of correlating thermal conductivity, heat capacity and density to the heating value. Even if the MKS reported false values for the butane isomers, the low quantities do not affect the

LHV calculation that much and therefore it follows the line quite nicely as well. The average errors for lower heating value was 0.57 MJ/m3 for the MKS sensor, and 0.51 MJ/m3 for the MEMS sensor.

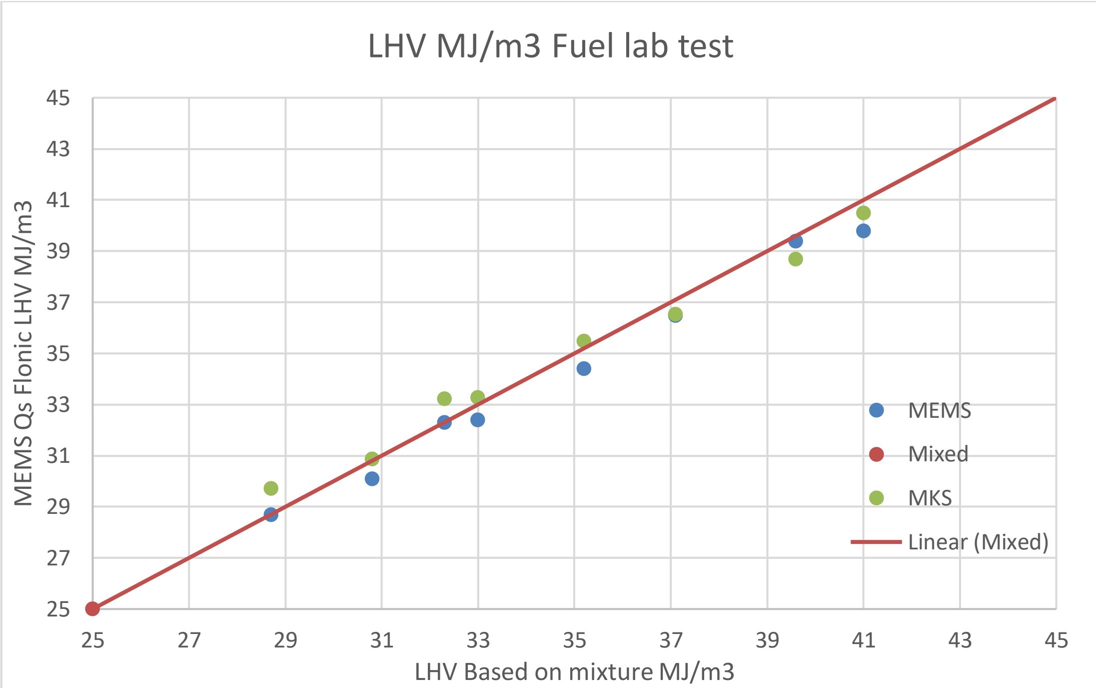

Figure 29 MEMS and MKS measured LHV compared to actual values

4.4 Results from the correction factor study

In Figure 30, the test points that were selected for this study are plotted against corresponding methane numbers, where each line represents a different test series. Although the variations are not near the same magnitude as seen in Toftlund, they are still quite parallel to each other, proving that the efficiency could be corrected according to what gas, the engine will be running on.

One of the drawbacks with this data, is the low amount of points per series. A series is a set of experiments with test points that has run consecutively. Preferably each series should contain of more than two points to see the real trend of change, as see in the series 1189-1192 and 1683-1685 where the efficiency is an exponential function of MN. To make an accurate prediction, more points per series would be needed, but for this study a simple linear equation was applied to the collected data to prove the idea. Actual values are hidden because of confidentiality reasons.

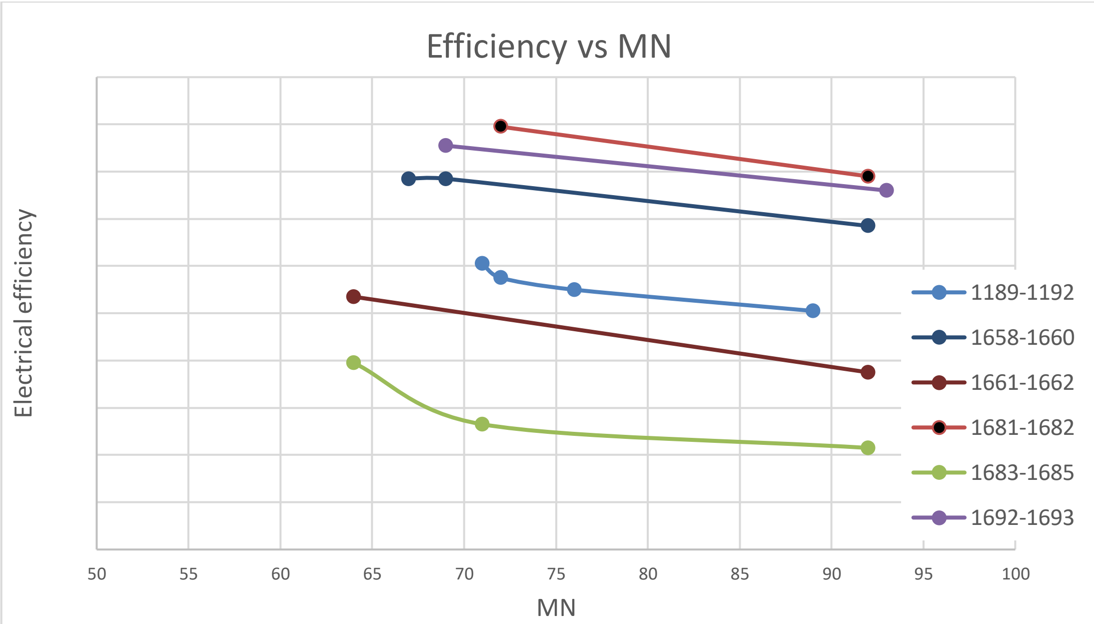

Figure 30 Electrical efficiency calculated according to Equation 11 vs MN for 10V31SG lab engine

For the 10V31SG lab engine from which the data was gathered, the mean value C_{eff} calculated according to Eq.(17) from the test points above 0.015. Which can be translated to 0.45% electrical efficiency loss or gain if the methane number would change by 30 units.

5 ASSESSMENT OF RESULTS

The purpose of this thesis was to study how natural gas quality influences a gas-fired engine's performance, and how it could possibly be counteracted by an engine control function.

Looking at the results from Toftlund, Figure 21, the efficiency changes are quite large. However, it is expected, according to the operating window theory, since the operating point does not move with the moving window. Since the supplied gas at the site does vary from time to time, a function to compensate for engine performance would be beneficial here. If a control function were to be implemented, an upgrade to the newer UNIC control system would be required. This opens for a business opportunity to sell such an upgrade, not only for this installation but for other, new builds and older ones as well. This is, however, quite and old engine and the variations are supposedly more noticeable for older engines compared to engines with newer technologies. As seen in the reference gas study, the 31SG laboratory engine did not show considerable differences in efficiency or NO_x emissions with different methane number gases. However, a typical trend with different settings could be noticed, proving the possibility to "recalculate" emissions and efficiency for changing gas qualities. All in all, the concept of the installation created at Toftlund is working in a satisfactory manner and could very well be used as a standard setup for the gas sampling and measurements.

Currently, the first choice for gas analysers is still the MKS. Initial testing with the MEMS Qs Flonic at the fuel laboratory showed quite promising values for the lower heating value, but for the methane number some improvements are still needed for correlating the measured parameters to the methane number. With the current accuracy it is not suitable for engine control use, but if the correlation could be improved for methane number it could be used as an alternative sensor to the MKS. Therefore, the tests with the newer version of the sensor will continue at the engine laboratory to gain a better picture of what its capabilities are.

The low methane number concept testing performed at Bermeo with the gas quality control enabled was shown to be useful for this project as well, even if there was no focus set on the performance of the engine in regard to methane number. The functionality testing was successful, and much of knowledge was gained about the challenges with sensor placement, mapping and the communication side. As such, the control function with ignition timing and boost pressure worked very well, and those aspects are probably the ones to focus on in the future regarding these kinds of controls.

To summarise the results according to the aim, a fully implemented engine control based on methane number is not finalised yet. However, the system using the MKS sensor for measurements and the said parameters for engine tuning is clear, as is the link between the sensor and engine control system. However, it is quite difficult to make any kind of "standardised" control function since the possibilities and needs are practically endless depending on the individual customer's needs. Regarding the market, this subject has received more attention and customers have also started to show interest in gas quality and how it affects the performance and reliability of their equipment. With the current setup used at the engine laboratory in Bermeo, tailored solutions based on the needs of a powerplant- or ship operator could be offered.

6 CONCLUSION AND FUTURE DEVELOPMENT

As the current setup with gas measurement, communication and control function is clear, further focus of the development work should be placed on more field tests, preferably with control applications in function. At the later part of this project, it was also revealed that all the future sold powerplant projects will include a gas quality sensor, which means that the only work required to get tuning based on methane number is software based. A strong candidate to push for is obviously the pilot installation in Toftlund, who already have been approached for a UNIC upgrade and are aware of the benefit it would bring. This would also require some parameter tuning and testing at the site to find the optimal settings for the ignition timing and boost pressure maps. The sensor in Toftlund is already installed, but for upcoming projects the placement of the sensor and gas lag issues should be further evaluated to ensure the reliability of the controller.

The internal project at Wärtsilä will continue to further develop the concept. Some of the primary things ongoing there is the follow up and testing of the second version of the MEMS Qs Flonic sensor, further development of the Wärtsilä Methane Number calculator and, of course, the implementation of the control function. Also, the work to drive the reference gas and correction factor idea forward will continue. Some other topics that might be of interest to investigate in the future are: (i) How the charge air humidity influences knock sensitivity and performance, (ii) Possible condensation problems with higher hydrocarbons, for this purpose a dewpoint calculation could be added to the methane number calculator, (iii) methane number and possible control function for dual fuel engines.

From the automation side, more tests will most likely be done within the 50SG low methane version project in the next few years. These should also be followed up and participated in, if possible, since considerable knowledge was received about what needs to be studied and what to test further.

SVENSK SAMMANFATTNING

Utveckling av en gaskvalitetsbaserad motorstyrningsapplikation

Inledning

I dagens läge koncentreras mycket av den energirelaterade forskningen till miljövänliga energikällor och skonsammare sätt att producera energi. För förbränningsmotorer innebär detta utmaningar med att utveckla nya teknologier för att minska på utsläppen, både i form av nya bränslen och förbättringar av nuvarande koncept. Gällande ottomotorer, som använder gas som bränsle, är det främst utsläppen av kväveoxider, koldioxid och oförbrända kolväten som undersöks och regleras.

Gasmotorerna drivs främst av naturgas som utvinns enligt samma metoder som råolja. Naturgas består främst av metan, men också av etan, propan, butan och i vissa fall även pentan och hexan. Naturgasens kvalitet beräknas enligt ett metantal som beskriver gasens antändlighet. Metantalet beräknas enligt gasens komposition och tilldelas ett värde mellan 0 och 100. I regel ligger metantalet för naturgas mellan 70 och 95.

Gasmotorerna optimeras under utvecklings- och produktionsskedet för att säkerställa pålitligheten, prestandan och utsläppskraven. I nuläget säljs motorerna som optimerade till en viss sorts gas (metantal), och därefter används den gas som finns att tillgå där motorerna placeras. Eftersom naturgas produceras över hela världen och utvecklingen driver nyare och ovanligare gastyper framåt, varierar kvaliteten mycket beroende på produktionsort och typ av gas. Det är i vissa fall problematiskt om gaskvaliteten inte motsvarar motorns inställningar, om metantalet är antingen lägre eller högre.

Med hjälp av nya mätteknologier kan gasens kvalitet analyseras tillräckligt snabbt och noggrant, för att i realtid utnyttja denna information för att styra motorn enligt kvaliteten på den gas som motorn då använder som bränsle. Genom att använda gaskvaliteten som en parameter i motorns styrsystem kan man säkerställa att motorn alltid är optimerad enligt det rådande metantalet.

Syfte

Syftet med detta arbete var att vidareutveckla det koncept som redan finns för realtidsmätningar av gaskvalitet till en fungerade kontrollfunktion med metantal som parameter. Forskningsfrågan delades in i två frågeställningar:

- Hur inverkar gasens kvalitet på en gasmotors verkningsgrad, knackegenskaper och kväveoxidutsläpp?
- Vilka parametrar ska ingå i en eventuell kontrolfunktion och hur ska den fungera?

Studien genomfördes med hjälp av dataanalyser, prestandaberäkningar samt gassensor- och motortester. Som sidostudie ingår även testandet av en ny gassensor som använder sig av fysikaliska storheter för att beräkna metantal, i motsats till traditionella sensorer som mäter gasens komposition. Även en referensgasstudie som baserar sig på kompensationsfaktorer för utsläpp och verkningsgraden i motsats till en kontrollfunktion ingår. Arbetet avgränsas till att endast omfatta Wärtsiläs gnisttända gasmotorer.

Metod och material

För att undersöka hur den inkommande gaskvaliteten påverkar förbränningsegenskaper hos en gasmotor studeras motordata och gaskvaliteten i en testinstallation i Danmark. I testinstallationen finns en gassensor som mäter den inkommande naturgasens metantal och värmevärde vid den inkommande gasledningen. Med hjälp av data från motorns styrsystem beräknas den elektriska verkningsgraden för olika metantal. Samtidigt studeras även knack- och utsläppsnivåer av kväveoxider från samma tidpunkter för att kunna avgöra hur väl motorn fungerar med olika gaskvalitéer. Dessa data används därefter som grund för att förstå hur en kontrollfunktion skulle behöva fungera för att kompensera för varierande metantal.

Utgående från dataanalysen från Tofltund utförs en serie motortester vid Wärtsiläs motorlaboratorium i Spanien. I dessa tester används en kontrollfunktion som justerar motorns förtändning och laddluftstryck enligt rådande metantal. Genom att blanda in propan i den naturgas som leds till laboratoriet sänks metantalet, och därigenom kan funktionens duglighet valideras. Testerna ingår delvis i ett annat projekt som automationsavdelningen utvecklat för ett lågmetantalskoncept för Wärtsiläs gasmotorer. Syftet med dessa tester är att möjliggöra övergången från naturgas till ren propan och etan. Spannet i metantal sträcker sig från 75 för naturgas till 35 för ren propan. Testerna innefattar inte finjustering för optimal prestanda, utan koncentreras främst till att testa kontrollfunktionens funktionalitet.

Som en sidostudie testas en gassensor, MEMS Qs Flonic. Denna givare utför sina metantalsberäkningar genom att först mäta gasens densitet, värmeledningsförmåga och värmekapacitet i jämförelse med den normala givaren som mäter gaskomposition med spektroskopi. Målet med dessa experiment är att studera om det finns ett sambad mellan gasens fysiska egenskaped och metantalet. Grundläggande tester görs i ett bränslelaboratorium för att testa sensorns funktion. Därefter installeras givaren i Wärtsiläs motorlaboratorium för att testas på längre sikt.

En annan sidostudie utgår från en teori att beräkna utsläppsnivåer och verkningsgrader enligt olika metantal som ett alternativ till att styra motorn. På så sätt skulle referensgasen vara en standard med vilken tillverkare skulle fabrikstesta sina motorer. Prestanda och utsläpp korrigeras med kompensationsfaktorer, enligt den gas kunden har specificerat. Beräkningarna görs enligt prestandapunkter för Wärtsiläs 31-motor och är relativt enkla, tanken är att endast bevisa att idéen kunde fungera.

Resultat och diskussion

De beräkningar som baserades på data från testinstallationen i Danmark visade att gaskvaliteten har stor inverkan på en motors verkningsgrad och kväveoxidutsläpp. I regel steg verkningsgraden med 1,5 procentenheter per 10 enheter lägre metantal. Motorn hade en lägre verknigsgrad vid högre metantal. Samtidigt som verkningsgraden ökar så stiger även NO_x-utsläppen och knacknivåerna. Detta är dock förväntat och vållar endast problem när motorn knackar för mycket och stannar på grund av säkerhetsskäl eller om kväveoxidvärdena överstiger det tillåtna. Å andra sidan lider motorn av försämrad verkningsgrad när gaskvaliteten är högre än vad motorn är optimerad till. Här skulle en kontrollfunktion kompensera för förhöjda värden av metantal och spara bränslekostnader.

Motortesterna med metantalsbaserad kontrollfunktion visade sig vara lyckade i den mån att funktionen gör de parameterändringar den ska när metantalet sjunker. Med denna funktion kan motorn köras på full effekt samtidigt som bränslet varieras fritt mellan naturgas, etan och propan. Detta är endast möjligt utan funktionen när motorn går på tomgång. Samtidigt gav testerna mer insikt i hur kommunikationen mellan motorns styrsystem, gassensorn, beräkningsmodellen och andra enheter borde utföras i framtiden. Ett av målen med testerna var att undersöka om det finns en fördröjning mellan det att sensorn läst av ett värde och att gasen leds in i förbränningsrummet. Någon större eftersläpning i tid mellan gasmätningen och när gasen verkligen förbränns kunde inte noteras under dessa tester.

Det visade sig inte vara möjligt att använda den testade MEMS Qs Flonic-givaren för motorstyrning. Sensorn klarade av att noggrant mäta de tre fysikaliska värdena samt att bestämma värmevärdet på utgående från dessa. För metantalets del var sambandet inte tillräckligt tydligen för att kunna utnyttja den i motorstyrapplikationer. Om beräkningsmodellen för gaskvalitet kunde vidareutvecklas vore denna typ av givare ett lämpligt alternativ till den nuvarande lösningen.

Från referensgasstudien kunde ett linjärt samband mellan metantal och verkningsgrad observeras. Ökningen och minskningen i verkningsgrad var dock mycket mindre än den som noterats i Danmark. Troligen beror detta på att de data som använts till denna studie kommer från en nyare motor med nyare teknologier och bättre kontrollsystem. Trots detta så kunde en kompenseringsfunktion härledas för verkningsgraden, även om skillnaderna var väldigt små.

Med tanke på forskningsfrågan uppnåddes målen till en viss del. Resultaten från Danmark gav mera insikt i hur naturgasens kvalitet inverkar på en motors prestanda och utsläpp. Kontrollfunktionen som testades i Spanien fungerade planenligt och möjliggjorde byten till gaser med lågt metantal, men kräver ändå vidareutveckling innan den kan implementeras i kommersiellt syfte.

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APPENDICES

Appendix 1. Toftlund data obtained from Wonerware Online application and used for performance calculations.

Start time		19:45	19:50	19:55	20:00	20:05	20:10	20:15	20:20	20:25	20:30	20:35
Filtered load signal	kW	5302	5300	5302	5300	5301	5305	5300	5302	5306	5300	5304
Gas flow	Nm3/h					Confidential						
Methane Number	WMN	88.9	88.4	85.2	80.5	77.3	74.7	73.2	72.5	72.5	71.5	71.5
Ignition angle	ddeg	123	123	123	123	123	123	123	123	123	123	123
Gas analysis	[vol-%]											
Methane	CH4	96.2	96.2	95.3	94.1	92.8	91.5	90.7	90	89.6	89.5	89.5
Ethane	C2H6	2.8	2.8	3.1	3.7	4.2	4.7	5.1	5.4	5.5	5.6	5.6
Propane	C3H8	0.1	0.1	0.3	0.8	1.2	1.6	1.9	2.1	2.2	2.3	2.3
i-butane	i-C4H10	0.1	0.1	0.2	0.2	0.3	0.4	0.4	0.4	0.5	0.5	0.5
n-butane	n-C4H10	0	0	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3
C5 lumped	n-C5H12	0	0	0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
Carbon Dioxide	CO2	0	0	0	0	0	0	0	0	0	0	0
Nitrogen	N2	0.5	0.6	0.7	0.7	0.8	1	1	1.1	1.1	1.2	1.2

Appendix 2. Test compositions used for MEMS fuel laboratory tests. Internal document.

	Methane	Ethane	Propane	n-Butane	N2	CO2	n-Pentane	MN	LHV
				Volume-%				-	MJ/m3
N3	0.8	0	0	0	0.2	0	0	107	26,7
N4	0.9	0	0	0	0	0.1	0	107	30,1
N5	0.8	0.1	0	0	0	0.1	0	84	32,7
N8	0.7	0.05	0.05	0	0.1	0.1	0	70	30,7
N10	0.7	0.02	0.02	0.02	0.2	0.04	0	66	28,6
N14	0.950	0.013	0.013	0.013	0	0	0.013	63	36,4
N15	0.777	0.059	0.029	0.013	0.072	0.043	0.007	62	35,0
N18	0.902	0.006	0.085	0.003	0.005	0	0	67	38,7